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ALTERNATE TECHNOLOGIES APPLICABLE TO PROXIMITY DETECTION ON MOBILE MACHINES IN UNDERGROUND COAL MINES

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ABSTRACT

There have been about 42 fatalities in underground coal mines between 1984 and 2015 where the victim was struck, pinned, or run over by a mobile machine (MM) such as a shuttle car, scoop, or battery hauler. MSHA has issued a proposed rule requiring proximity detection systems (PDS) on MMs in an effort to prevent future fatalities. Currently approved PDSs use electromagnetic (EM) technology to detect the presence of a miner and impose machine controls to prevent contact. The disadvantages of an EM-based PDS on MMs include the need for a miner-wearable component (MWC), environmental interferences, EM interferences from other devices, and low localization range and accuracy. NIOSH researchers are investigating alternate technologies that could improve the capabilities of the current PDSs. Many technologies were reviewed, and NIOSH researchers identified RFID, LIDAR, RADAR, ultrasonic detection, and computer vision as candidates for PDS development. The performance characteristics of each technology and its applicability to an underground mining environment will be discussed, along with international developments and implementations, and the concept of sensor fusion.

INTRODUCTION

PDSs provide safety to mine workers by detecting their presence (and in some cases location) around a machine. These PDSs provide a warning zone, which triggers an alarm, and a stop zone, which halts the machine before it contacts the miner. The Mine Safety and Health Administration (MSHA) issued a final rule requiring that PDSs be installed on all continuous mining machines (CMMs) on the working section, with the exception of full-faced machines, according to a phase-in schedule for newly manufactured and existing equipment [1]. The PDSs that were designed for CMMs have since been adapted to other mobile machines. Mobile machines include scoops, which are used as general utility vehicles, as well as coal hauling machines, such as shuttle cars, ram cars, and continuous haulage systems. MSHA has examined all accident reports from 1984 to 2014, and determined that 42 fatalities could have been prevented on mobile machines had a PDS been installed [2]. As such, MSHA issued a proposed rule that would require mobile machines on working sections (with the exception of longwall sections) to be equipped with a PDS. This rule would follow a phase-in schedule for newly manufactured and existing equipment.

Currently available PDSs are based on electromagnetic (EM) technology. NIOSH researchers developed a shell-based magnetic flux density distribution model [3] for determining the position of a miner near a machine. A typical system would consist of four generators positioned around the perimeter of the machine. Each generator is a coil of insulated wire wrapped around a ferrite core. The magnetic field strength is proportional to the current running through the coil. Miners working on the section have an MWC, which is a transceiver that measures the field strength emitted by the generators and transmits a data packet over an RF link which contains the field strength reading to the PDS controller mounted on the machine. The magnetic field generators are pulsed sequentially such that the MWC can identify which generator's field strength it is reading. This type of system utilizes the principle of magnetic flux density: the closer the MWC is to the field generators, the higher the field strength reading. Thus a miner's presence can be determined once he gets too close to the machine, because his MWC will measure a magnetic flux density beyond a certain threshold. These thresholds are utilized on a per-generator basis to "shape" the fields for both warning and stop zones around a machine, as illustrated in Figure 1.

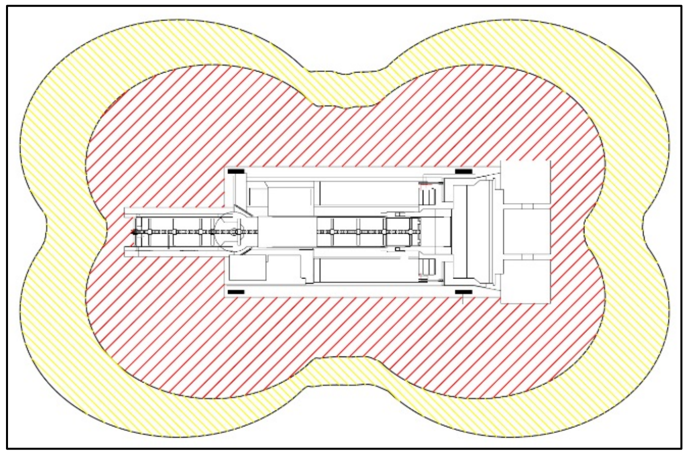

Figure 1. Representation of a CMM equipped with an EM-based PDS, showing warning (yellow) and stop (red) zones.

Due to the differences between CMMs and MMs, such as travel speed and exposure to a variety of environmental conditions, EM-based PDSs could be modified to improve performance and reliability. In addition, other technologies exist that could provide additional benefits for PDSs on MMs. These technologies are described in this paper, along with their inherent advantages and disadvantages relative to PDS implementation.

ELECTROMAGNETIC PROXIMITY DETECTION SYSTEMS ON MOBILE MACHINES

NIOSH has conducted numerous field evaluations and studied the performance of EM-based PDSs installed on CMMs [4, 5]. The results suggest that PDSs on CMMs provide adequate protection to the miners. In an effort to identify the applicability and transferability of EM-based PDSs on to MMs, NIOSH has conducted field evaluations of PDS-equipped MMs. These field evaluations consisted of having an operator drive the mobile equipment towards a MWC positioned in an entry or crosscut. In most cases, the PDS did stop the machine before it struck the MWC. However, three primary concerns have arisen with respect to EM-based PDSs for use on mobile machines in underground coal mines: environmental effects, electromagnetic interference (EMI), and general performance characteristics.

Environmental Effects

Because EM-based PDS is based on the principle of magnetic flux density for ranging, the system is also susceptible to environmental effects, which skew the accuracy of this principle. During recent field evaluations NIOSH researchers observed some phenomena not measured in previous field studies, including

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diminished performance in the vicinity of metal mesh and powered cables on the working section. These occur due to mutual inductance (MI), which is the linking or coupling of a magnetic field from the generator coil to metal objects or wires in close proximity. It should be noted that the following details are observations discovered during field evaluations, but were not tested under a peer-reviewed field test protocol.

Figure 2 shows an illustration of observed discrepancies with PDS performance near a CMM trailing cable. It was observed that warning and stop zones could be incurred at much greater distances than the PDS set points. Three different MWC positions are shown in this graphic: near the trailing cable, in contact with the trailing cable, and in contact / near the loop of trailing cable. The actual positions are noted, along with the PDS-triangulated positions as observed on the PDS graphical user interface (GUI). When the MWC was positioned within a few inches of the trailing cable at some distance down the entry, it would incur a false warning zone. When the MWC came into contact with the trailing cable, it would incur a false stop zone. Similarly, when it was within a few inches or touching a loop of trailing cable, it would incur a false stop zone. An additional trailing cable discrepancy not depicted in the graphic was observed when a battery hauler traveled underneath a powered cable hung along the roof. A MWC positioned near the rib mesh in the crosscut that the cable ran through was able to incur a false stop zone on the battery hauler. The circumstances described by these findings are not considered to be hazardous to miner safety because they do not allow any unsafe machine actions. These scenarios, however, could substantially hinder production. It should be noted that PDS manufacturers provide guidance to maintain minimum separation distances from trailing cables and metallic objects.

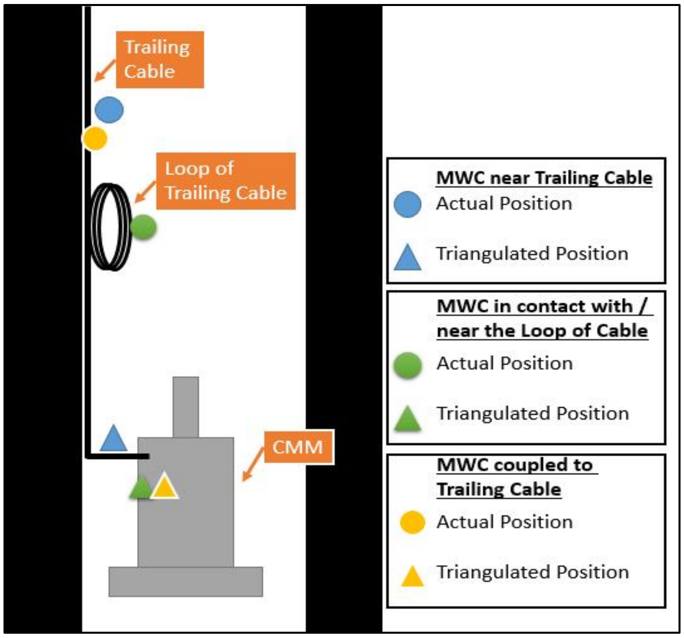

Figure 2. Illustration of observed discrepancies with PDS performance near a CMM trailing cable. Circles show actual positions, and triangles indicate triangulated positions per the PDS GUI.

Further triangulation inaccuracies were observed in the vicinity of metal mesh installed on the roof and ribs, as illustrated in Figure 3. When the MWC was positioned within a few inches or in contact with rib mesh, the triangulated position as observed on the PDS GUI showed the MWC on the opposite side of the entry. This specific scenario was observed in a section that used a double layer of rib mesh. This inaccuracy could be hazardous to miner safety in the event that the machine misidentifies miner presence and thus fails to prohibit the appropriate machine interventions when the machine drives or pivots towards a miner.

PDS systems are tuned for the mine section in which they are deployed. A PDS that is deployed in a section with double mesh layers may be tuned differently from a section with only a single mesh layer, or no mesh. As a part of normal operation, mobile machines may often traverse sections that have some mesh, a single layer of mesh, and others that have double layers of mesh. Our observations suggest that the metal mesh influences the performance of PDSs significantly, and it should be noted that the PDSs have no means to automatically identify mesh conditions in the section they are operating in. Thus the machine may provide sufficient safety interventions in one part of a mine, but not in another.

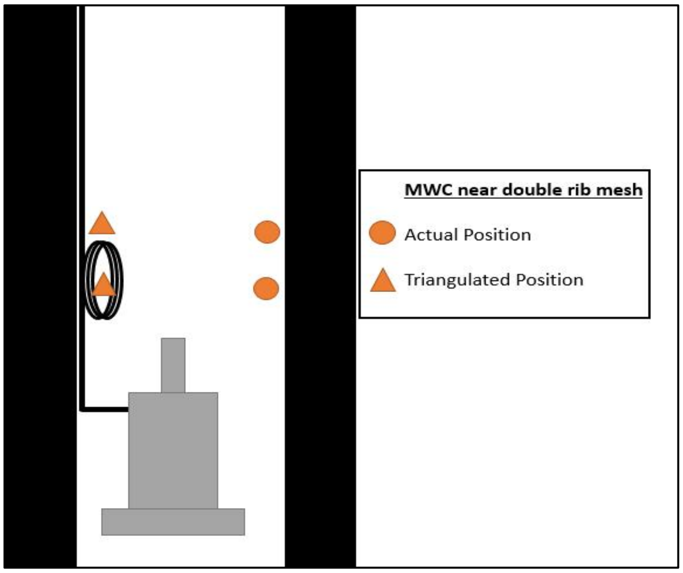

Figure 3. Illustration of observed discrepancies with PDS performance in a mine section with double rib mesh. Circles show actual positions, and triangles indicate triangulated positions per the PDS GUI.

Another incident discovered in a field evaluation involved a MWC at some distance down a crosscut that incurred a false stop zone and prevented a battery hauler from traveling down an entry, as illustrated in Figure 4. This was experienced at distances of up to 52 ft. down an entry for both single and double layers of metal rib mesh. As shown in the graphic, the MWC was positioned along the center of a crosscut, and did not need to be near or touching the mesh to produce this scenario. The battery hauler was not able to pass by the crosscut until the MWC was moved further away. The circumstances described by this finding are not considered to be a safety hazard because they do not allow the machine to perform any unsafe actions.

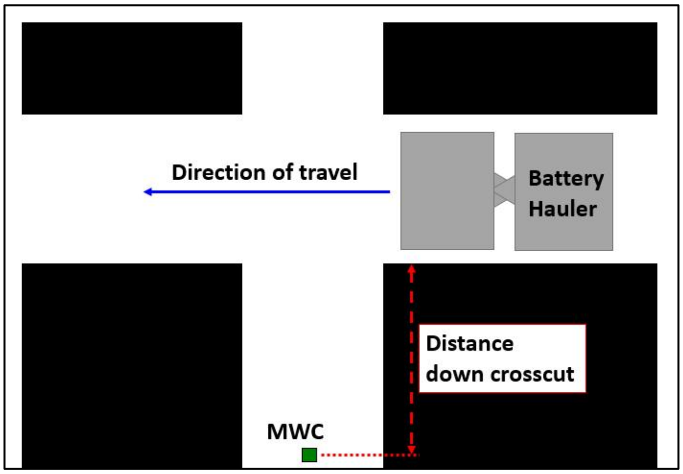

Figure 4. Illustration of an observed discrepancy with PDS performance in mine sections with both single and double layers of metal mesh on the ribs and roof.

Figure 5 illustrates another scenario where a crosscut was rendered impassible due to a PDS discrepancy. It was observed that when a battery hauler attempted to pass by a crosscut with a power

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station, a MWC located in any position down the crosscut would incur a false stop zone. There was a stopping behind the power station at the mine where this was observed, which blocked the ability to test further distances down the crosscut. This scenario is not considered to be hazardous to safety, though it could be a substantial hindrance to production.

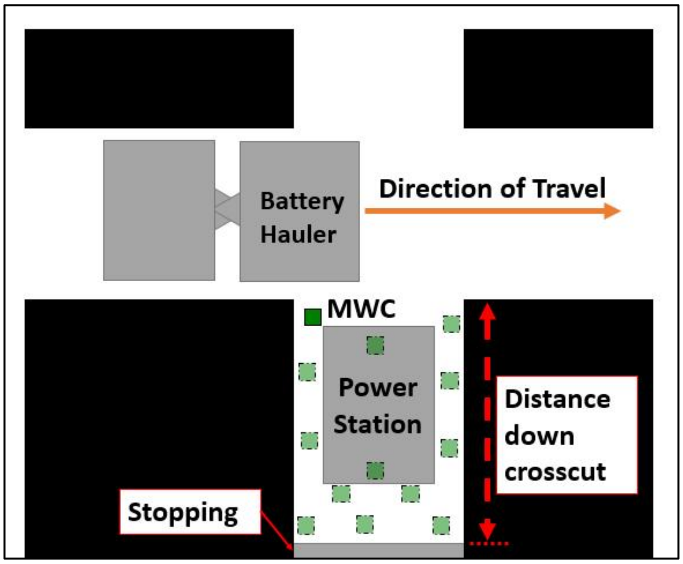

Figure 5. Illustration of an observed discrepancy with PDS performance in the vicinity of a power station. The green icons indicate the MWC location. The shaded icons represent all of the locations tested.

In some of these circumstances, software modifications to the PDS are necessary to enable reliable operation. In other instances, adjustments to mine operations are necessary. These design parameters and potential corrections are being further investigated by NIOSH.

Electromagnetic Interferences

NIOSH researchers have observed electromagnetic interferences (EMI) from continuous personal dust monitors (cPDMs) [6],that hinder the performance of PDSs significantly. The cPDM is a belt-worn monitor that takes interval samples for respirable coal dust. It was discovered by mine sites and brought to the attention of NIOSH that when miners wear their cPDM and MWC close together, the MWC begins to behave erratically. In some cases, this would permit the miner to walk all the way up to the machine without incurring a warning or stop zone, which poses a significant safety hazard. This behavior has been has been observed with the cPDM, but could potentially occur from other electronic devices that emit spurious electromagnetic noise within the operating frequency of the PDS.

NIOSH conducted laboratory testing of one PDS manufacturers MWC to measure its susceptibility to EMI, along with measurements to identify the EMI being produced by a cPDM, and found that it was best to keep the cPDM and MWC at least 6 inches apart in order to preclude EMI. This finding correlates with the recommendations by the PDS manufacturers [7, 8] of maintaining 6 inch separation distance.

A prototype shielding pouch for the cPDM was developed by a PDS manufacturer in an attempt to mitigate the EMI effects. Lab tests showed that only a 2” separation distance was needed to prevent EMI effects. However, underground testing at one mine showed increased EMI effect from the use of the pouch. The mine had mesh on the roof and ribs in the mine section used for testing. Depending on the position around the machine the shielded pouch could actually cause EMI to be experienced at separation distances of up to 13 inches. NIOSH is currently investigating this phenomenon.

Improved Performance Characteristics

Additional performance concerns with respect to the PDS itself include system response time, stopping distances, and repeatability. An EM-based PDS operates by sequentially pulsing the magnetic field generators, with the MWCs measuring the field strengths and then transmitting that information back to the PDS controller. The system response time is the time delay between when a change in physical MWC position and when the machine measures the change in position. This will vary between PDS manufacturers, but systems may update readings at a rate of 4 Hz. Mobile machines, such as shuttle cars and battery haulers, can travel at speeds of up to 6 mph, which means that the machine could travel up to 2.2 ft before an updated measurement is achieved.

An additional uncertainty is the distance traveled during braking, which will vary based on machine, proximity system, loaded or unloaded condition, and mine floor conditions. This includes the distance traveled from the time a MWC is identified in a stop zone to when the brakes are actually applied, and the sliding distance. It is expected that a machine will experience little to no sliding on a level, dry floor, but could experience some sliding with a wet floor, or on a slope.

The combination of environmental effects, EMI, and performance criteria concerns require further research to develop the PDS to provide the best protection to miners.

ALTERNATE TECHNOLOGIES

In an attempt to identify alternate technologies that could improve or complement existing PDSs, NIOSH researchers have identified a number of sensing technologies worthy of investigation. It is possible that an improved PDS will be a fusion of a number of sensing technologies, as opposed to a single-sensor-type system. Potential sensing technologies that could be further examined are discussed below.

RFID

Radio frequency identification (RFID) utilizes EM fields to identify and track objects using an RFID reader and tags. The tags are attached to the objects that are to be tracked, and transmit encoded radio signals to the reader. There are two types of RFID tags: active and passive. Active tags have their own power source and operate at further distances than passive tags, which collect energy from the RFID reader and must be near the reader. There are a variety of ranging calculations that could be used to determine distance between the reader and the tag. One of the more commonly used methods is referred to as *time of flight (ToF)*, which measures the time from when a signal is transmitted until the time when the response is received. This information, along with the propagation speed of the signal, can be used to assess the distance from a tag to a reader. Similarly to magnetic field-based proximity detection systems, the use of multiple readers could allow for the tags position to be determined through trilateration or fingerprinting.

The pros and cons of RFID are shown below in Table 1. This technology could provide localization that is similar in nature to magnetic field PDSs. As such, some problems will be common amongst the two, including: EMI, environmental effects, and general performance.

Table 1. Pros and cons related to RFID.

Pros	Cons
Can detect objects outside of its line of sight.	Requires object that is being tracked (i.e. human) to wear a tag.
Lower-frequency units can provide detection at a close range, while higher-frequency units can provide detection at greater distances.	Will be subjected to environmental and electromagnetic interferences.
Performance not hindered by dust or smoke.	Requires multiple readers for localization.

RADAR

Radio detection and ranging (RADAR) is a method for detecting the range of objects by transmitting a radio signal and then measuring the reflection. From the reflection, the distance from the radar unit to the object can be determined. There are two primary measurement methods for a radar sensor, which include pulsing and continuous

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wave. Pulsing radar works on the principle of ToF, and measures the time between the transmission and the return with the distance being proportional to this time. The continuous wave method works by transmitting a radar signal of a known, stable frequency, and then measuring the Doppler shift of the reflected signal. The Doppler shift indicates the change in frequency of the reflected signal, which is proportional to the speed of the target. The pros and cons for RADAR are shown below in Table 2.

Table 2. Pros and cons of RADAR.

Pros	Cons
Contact-free detection.	Sensors are directional: will only detect objects in line of sight.
Different units can offer wide-angle, medium-range detection, while others can offer narrow-angle, long-range detection.	Will be subjected to environmental and electromagnetic interferences.
Works well in dirt and dusty environments.	Detection is not specific to a known target (i.e. human). Will detect all obstacles.
Can provide directional detection with a single sensor	Requires multiple sensors to achieve localization.

LIDAR

Light detection and ranging (LIDAR) is a ranging method based on laser technology. These units typically involve a laser with an oscillating mirror that enables the unit to conduct ranging in 2D space. 3D laser scanning can be achieved with a multi-axis unit. The operating principle is based on ToF: the unit emits a pulse of laser energy and then measures the response using a photodetector. Once one position has been measured, the unit oscillates to the next position, and then performs another measurement. This process is repeated over the oscillating range of the unit, allowing for a 2D measurement sweep to be recorded. LIDAR units can achieve up to 360° horizontal field of view with measurement rates up to 50 Hz. The pros and cons of LIDAR are shown below in Table 3.

Table 3. Pros and cons of LIDAR.

Pros	Cons
Contact-free detection.	Will detect any object in its line of sight (not specific to humans).
Different units offer wider or narrower fields of view to provide sufficient resolution and detection.	Performance could be hindered by dust and smoke.
Provides high data rate for great measurement detail and accuracy.	Cannot detect through barriers.

Ultrasonic

Ultrasonic sensors (USSs) operate on the principle of transmitting a high-frequency sound wave at an object, and then measuring the reflected echo off of the target. The response is linear with the distance between the USS and the object. This is based on ToF along with the propagation speed of the sonic wave. These sensors work well in near-range ranging applications. USSs are directional, and provide a narrow beam detection range; thus numerous USSs would be required on a machine to provide adequate coverage. The pros and cons of USSs are describe in Table 4 below.

Table 4. Pros and cons of USSs.

Pros	Cons
Contact-free detection.	Low-density materials can absorb sound waves.
Accurate in the short range (<3 m).	Sensor saturation could occur if there is too much noise in the area.
Work well in dirt and dusty environments.	Environmental changes (temperature, humidity, could affect performance).
Cost-effective and simple to integrate numerous sensors into a detection system.	Cannot detect through barriers.
	Sensors are directional: will only detect objects in line of sight.

Computer Vision

Computer vision is a broad and growing field of computer science and robotics that utilizes visual data captured from cameras to detect and analyze obstacles and environments. Monocular cameras are not capable of providing ranging without using a stereo camera system (use of multiple lenses and image sensors). However, cameras are capable of providing visual indicators to operators to enable better use of their equipment. Furthermore, computer algorithms can be developed such that mine workers can automatically be detected within the camera's field of view. This would apply to standard black and white images as well as thermal imaging cameras, as computer vision algorithms can be developed to detect edges and shapes, or to identify temperature thresholds that would indicate the presence of a miner. The pros and cons of computer vision are shown below in Table 5.

Table 5. Pros and cons of computer vision.

Pros	Cons
Contact-free detection.	Cannot measure range with monocular cameras.
Can develop custom computer vision algorithms.	Can only detect objects in the camera's field of view.
Thermal imaging cameras are not obstructed by smoke or dust.	Depth of view is fixed.

Ultra-Wideband

Ultra-Wideband (UWB) is a radio technology that transmits data over a large bandwidth greater than 500 MHz and does not interfere with conventional narrowband transmissions. UWB signals are highly immune to noise and interference, allowing them to work well for ranging applications such as proximity detection. Ranging is accomplished based on the ToF principle to measure the time it takes for transmission between two units. Accuracy is achievable down to 5-10 cm. The pros and cons of UWB are shown below in Table 6.

Table 6. Pros and cons of UWB.

Pros	Cons
Immune to MI and noise.	Cannot detect through barriers.
High accuracy.	Network congestion.
Work well in dirt and dusty environments.	

SENSOR FUSION CONSIDERATIONS

Current PDSs are based solely on EM technology—that is, they utilize only the magnetic fields generated by the PDS to determine miner presence and location. Based on the advantages and disadvantages of the PDS technologies discussed, NIOSH researchers hypothesize that an improved PDS will be a combination of multiple technologies. This is referred to as a sensor fusion system, which implies the integration of multiple sensing technologies. Sensor fusion systems operate using the advantages of each sensing technology to make up for the disadvantages of others.

An example of a sensor fusion system could include both LIDAR and RADAR sensors to provide accurate, high-level detail (LIDAR) and still detect through dust or smoke (RADAR), which is similar to a concept for military unmanned ground vehicles proposed by the Agency for Defense Development, Republic of Korea [9]. Another possibility would be to develop a system with thermal imaging computer vision and RADAR. This system could detect obstacles in various conditions (RADAR), and the computer vision element could provide validation of the obstacle. This is similar in nature to the concept proposed by Wang et al. regarding obstacle detection for autonomous ground vehicles [10]. Additional research has been conducted on the detection of pedestrians in underground mining using a thermal imaging camera for identification and a ToF camera for ranging [11].

DISCUSSION

Taking into account the advantages and disadvantages of different technologies and the known challenges with EM-based PDSs,

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a single-senor-type system may not suffice, but rather, a sensor fusion system may be the most appropriate. Some mines are utilizing EM-based PDSs in their mines on MMs and have developed implementation strategies based upon continuous tuning and modifications. Other types of technologies may help reduce some hardships with PDS implementation on MMs and improve the protection of miners.

An example of an existing sensor fusion PDS system is the Becker Collision Awareness System (CAS), which is a PDS used internationally. The Becker CAS is based on EM to provide coverage close to the machine, HF RFID to provide coverage beyond the close-range, and an ultra-high frequency (UHF) RFID to provide long-range coverage. This system utilizes the advantages of each technology to provide a robust system to prevent accidents from occurring.

Sensor fusion systems could consist of a combination of EM, cameras with computer vision, and RADAR such that multiple measurements are utilized for detection. These systems could be utilized to provide redundant detection and ranging with validation. RADAR could mitigate some of the environmental and EMI effects that hinder performance of EM systems, while the cameras with computer vision could provide validation of obstacle detection, and the EM could provide coverage through brattice cloth and around corners. It should be noted that EMI and environmental factors at different frequencies could hinder RADARs performance

This discussion is provided merely as an example and an analysis, and should not be construed as a recommendation for replacing current PDSs. Further research and development is necessary.

CONCLUSION

Existing PDSs are based on EM technology. NIOSH researchers have observed during field testing a number of disadvantages of these systems, including environmental interferences through metal mesh and power cables, electromagnetic interferences through other electronic devices, and general performance concerns associated with system response times. NIOSH researchers identified a number of technologies that could be used to support future developments of advanced PDSs to improve the capabilities of the current PDSs. Future research and development is necessary.

DISCLAIMER

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

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