

## Determining Proximity Warning and Action Zones for a Magnetic Proximity Detection System

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**Abstract** — Researchers at the National Institute for Occupational Safety and Health (NIOSH) are developing intelligent software for use with electromagnetic proximity detection systems. The technology accurately locates workers around mining machines in real time. With the accurate locations of the workers around the equipment being known, their safety status can be evaluated. If a worker is located dangerously close to a machine, the machine can be partially or completely disabled to protect the worker from striking, pinning and entanglement hazards according to pre-defined logic. The technology is particularly applicable to mobile underground mining machines which offer difficult safety challenges in that operators generally work in close proximity to these machines in very restricted spaces. With use of the intelligent proximity detection system, nuisance alarms and failures to alarm are also expected to be sharply reduced. An effective proximity warning and action zone scheme is necessary for safe implementation and will improve the acceptance of a magnetic proximity detection system by underground workers.

**Index Terms** — mining equipment, magnetic sensors, sensor systems, sensor fusion, occupational safety.

### I. INTRODUCTION

Operating large mobile equipment such as a continuous mining machine (CMM) is an often-hazardous job that workers perform in underground coal mining operations. Some of the conditions that make the job hazardous are the potential for roof falls, the close proximity of large moving machines, decreased visibility due to low lighting, dust, and noise generated by the mining process. In addition to the task of mining coal, machine operators must focus attention on their own position, the location of other crewmembers, and the proximity of the machine to the crew. Since the mining environment is dynamic, creating physical barriers to keep operators out of the unsafe zones is not feasible. Nevertheless, there are unsafe areas that the remote control CMM operators and other workers must avoid. Some areas are clearly defined, such as beyond supported top which is defined by the last row of bolts supporting the roof. Previous NIOSH research [1] identified safe and unsafe zones for the operator near the CMM.

In the past, operation of CMMs was performed from the machine cab in a seated position. In the 1980s, new

technology enabled the transition to remote control of the mining machines. By removing the operator from the machine cab, several safety and health hazards associated with having the operator near the coal face were alleviated. With remote-control capability, operators are now free to position themselves for better safety and visibility of the workplace. Typically, operators position themselves behind and to one side of the CMM during cutting operations. During tramming, the operator walks near the rear of the CMM in high coal seams where the machine is less of an obstruction. In low coal seams, the operator frequently trams the continuous mining machine while walking or crawling in front. Figure 1 illustrates these positions.

Previous research [1] included surveys of positions that CMM operators chose while performing cutting and tramming operations. Figure 1 and Figure 2 show the various positions chosen by CMM operators.



Figure 1 - Cutting work positions.

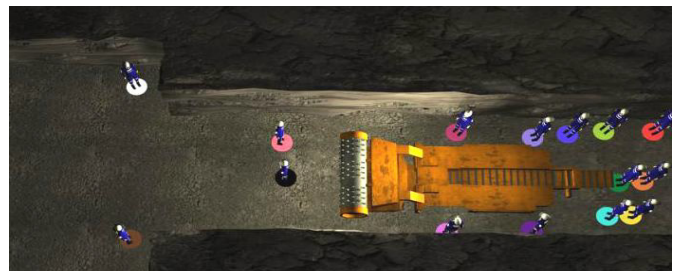


Figure 2 - Work positions dur

Unfortunately, operators have the tendency to step beside a moving CMM for a better view during forward, reverse, and turning movements while cutting coal or tramming. Adding to the hazards of operating a CMM is the restricted workspace with reduced visibility. The mine work environment, especially in low coal seams, puts CMM operators and helpers in awkward work postures for a job consisting of tasks that requires quick reactions to avoid being struck by moving equipment.

The Mine Safety and Health Administration (MSHA) recommends that miners avoid a set of “red zones” that define dangerous areas near the CMM. These zones help CMM operators understand and avoid potentially dangerous areas within the turning radius of the machine. Although this recommendation was developed in the late 1990s, fatalities and injuries continue to occur with striking and pinning accidents involving the CMM. This suggests that violations of the red zone recommendation occur. A technological control to prevent the CMM from making hazardous motions with workers nearby could reduce striking and pinning accidents. A promising technology for this purpose is electromagnetic proximity detection, which utilizes magnetic fields to determine the proximity of workers to the machine.

#### A. Background

Remote control operation of a CMM requires operators to divide their attention and process much information simultaneously. Defining and prioritizing what cues and feedback are needed and determining where operators focus their attention can be used to develop safe, realistic operating procedures. The cues that operators use are primarily visual but will sometimes include auditory information to compensate when visual cues are blocked. The mining environment is a unique safety challenge due to its dynamic nature, and there are many hazards and much operational information that must be continually monitored by the CMM operator. The ability to process and utilize information, in particular the visual cues the operator uses, is an important component of the human-machine system. Safe and effective control of the system is dependent upon the worker properly sensing pertinent information and processing it to make the right decisions. Experienced miners have expanded their knowledge, skills, and abilities to perform safely and effectively. By identifying the specific cues used by these experienced operators, interventions and training methods can be designed to improve safety for all operators.

Previous studies [1] identified and defined visual attention locations (VALs) associated with remote operation of CMMs. In this research, VALs are particular locations needed and visually used by the operator for machine control and operation. Operators need to consider safe work position, sounds, vibrations, and VALs such as machine orientation, operating characteristics, and other visual cues within the

work environment to perform their job effectively. These factors have to be accommodated concurrently when considering a safe operator location. The optimum work location for an operator may differ depending on the length of cut, visibility, roof condition, ventilation, and avoidance of moving machines. This research identified operator work positions and VALs needed during mining operations or when moving to a new location. Analysis of the data defined the operators’ risk of injury relative to task, equipment, and workplace environment. In addition, the data indicated that a major contributing factor to CMM related injuries is operators positioning themselves in a hazardous position in order to see cues or VALs.

The results of digital human model simulations [2] showed that operators of CMMs greatly reduced their likelihood of being struck or pinned by a CMM if they maintained a 3-foot minimum distance. These simulations indicated that reducing the speed of the CMM did not significantly reduce the chances of personnel being struck or pinned. As shown in Figure 3, the results indicated a 40% decrease in incidents when the initial position of the operator was 3 feet from the CMM compared to a 2 foot distance.

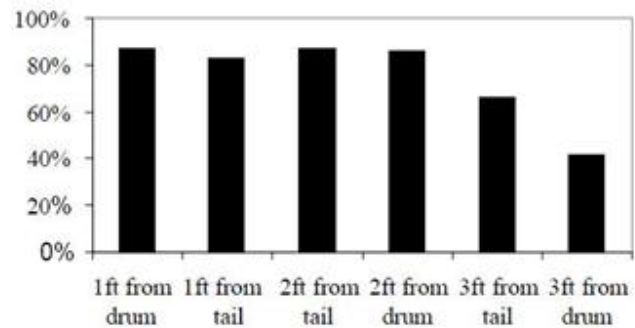


Figure 3 - Percent struck vs. distance from CMM.

Some of the technologies utilized in surface mining and in other industries for proximity detection systems include the Global Positioning System (GPS), and radar-, laser- or ultrasonic-based distance sensors. Thus far, these technologies have not been effective in underground mines, where GPS is unavailable, and the constant close proximity of mine walls makes the use of the other sensors extremely difficult.

Another possible solution is the use of Radio Frequency Identification (RFID) technology. Many industries commonly use RFID for tracking the movement of personnel, supplies, and equipment. It is also currently in use in the mining industry for tracking the movements of people, equipment, and supplies through the mine. These systems are capable of providing information on whether a tag worn by a person or mounted on a machine is within a set range of the transmitter, but are currently ineffective at providing an accurate distance from the transmitter. This makes RFID technology unsuitable

for measuring the position of a person near a moving machine.

Another emerging technology that may be applicable to this problem is intelligent video systems, utilizing either single-camera or stereovision and complex algorithms to identify and locate people and machines in the visual scene. However, application of this technology in the underground mining industry is likely to be very challenging due to poor lighting, dust, and the extreme difficulty in keeping the cameras clean.

Currently in the United States, the available systems for underground mining use either magnetic fields or radio frequency technology to alert miners when a machine is close to another machine or a person. On CMMs, the operator receives visual and audible warnings upon entry into the warning zone; further approach into the danger zone causes the equipment to shut down.

Recent interviews with the mining community [3] indicate that shutting down the equipment is perceived as more of a hindrance than a safety feature. NIOSH researchers are developing technology that adds a measure of intelligence to these systems. The NIOSH intelligent proximity detection system (iPDS) accurately determines miners' positions relative to the CMM and responds by disabling only the specific machine functions that could cause injury.

## II. CMM ACTION ZONES

The presence of a miner in the proximity of the iPDS is detected through the wearing of a Personal Alarm Device (PAD). This PAD reports information to the iPDS that allows the system to determine the PAD's location. Once the position of a miner is identified, the NIOSH iPDS 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 a mining 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. The location of miners near the CMM is determined using commercially available proximity detection hardware along with unique software previously developed by NIOSH [4].

By only preventing the actions that could cause an injury, miners can select where they position themselves, and safe mining is allowed to continue uninterrupted. 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 should be enhanced.

### A. Zone Definition

As an example, and to demonstrate the operation of this system, a set of zones has been defined with associated shutdown logic actions for the NIOSH prototype system. This is one possible implementation and should not be construed as a recommendation for all mines. The conditions and standard operating procedures at a given mine should be considered when designing the logic that controls the iPDS. The seam height, haulage system, roof control plan and other mine-specific safety considerations all have an impact on safe locations near the CMM and should be taken into account in the implementation of an iPDS. Figure 4 shows the example zones defined for the prototype iPDS and TABLE 1 gives the associated machine functions that are disabled for each of these zones. Note that it is possible for the zones to overlap. The implication of overlapping zones is that a person could be located in more than one zone simultaneously; in which case, all hazardous machine motions associated with either zone should be blocked. This is further complicated by the consideration of uncertainty in operator location as discussed in the following section.

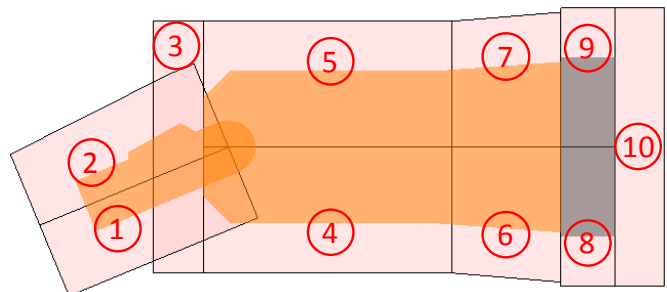


Figure 4 - Example configuration for zones.

TABLE 1 - EXAMPLE CONFIGURATION FOR MACHINE FUNCTIONS DISABLED BY ZONE.

		Zone									
		1	2	3	4	5	6	7	8	9	10
Tram	both forward										X
	right only forward	X			X			X		X	X
	left only forward		X			X	X		X		X
	both reverse	X	X	X							
	right only reverse	X	X	X		X	X		X		
	left only reverse	X	X	X	X			X		X	
	right forward/left reverse	X		X	X			X		X	X
	left forward/right reverse		X	X		X	X		X		X
Conveyor	raise	X	X								
	lower										
	swing right	X									
	swing left		X								
Cutter head	raise							X	X	X	
	lower							X	X	X	
Gathering pan	raise							X	X	X	
	lower							X	X	X	
Cutter motor								X	X	X	
Conveyor motor		X	X	X							
High speed tram		X	X	X	X	X	X	X	X	X	

### B. Uncertainty in Operator Location

Experiments with the NIOSH prototype iPDS have indicated that the position of a PAD can be determined to within an accuracy of 20 to 50 cm. In addition, other errors in the position are introduced by factors such as where the miner wears the PAD and the posture of the miner. Therefore, the PAD position should not be considered a single point, but rather as a circle with an uncertainty radius,  $r$ .

The task then becomes to determine whether this circle intersects a given zone. As mentioned in the previous section, it is possible for a PAD to be located in two or more zones simultaneously. Figure 5 demonstrates how this can occur for two arbitrary, adjacent zones  $X$  and  $Y$ . In this figure four PAD positions are indicated as circles of radius  $r$ . TABLE 2 shows the interpretation of each of these PAD positions including which hypothetical machine functions should be disabled. If a PAD is located in multiple zones, all machine functions associated with any zone in which the miner might be located should be disabled.

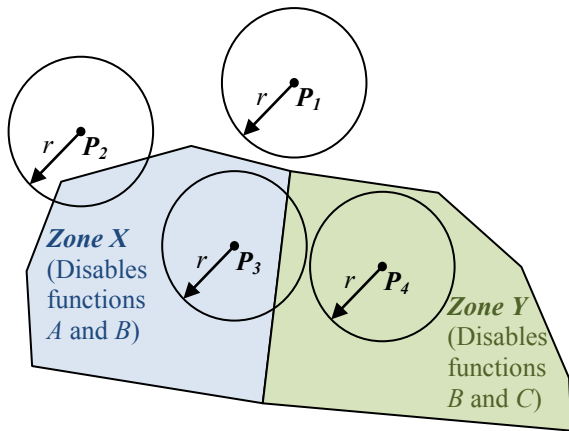


Figure 5 - Hypothetical example showing two arbitrary zones and 4 PAD positions with uncertainty radius  $r$ .

TABLE 2 – ZONES IDENTIFIED AND FUNCTIONS DISABLED FOR HYPOTHETICAL EXAMPLE SHOWN IN Figure 5.

PAD position	PAD located in zone(s)		Machine functions disabled		
	X	Y	A	B	C
$P_1$					
$P_2$	X		X	X	
$P_3$	X	X	X	X	X
$P_4$		X		X	X

### C. Implementation

In the NIOSH prototype system, the algorithm for determining the PAD location zones is as follows. Each zone is defined as a convex  $N$ -sided polygon. The vertices of the polygon,  $v_i$  ( $i = 1 \dots N$ ), must lie in the horizontal plane and must be defined in the clockwise direction. The triangulated PAD position is  $P$ , and the PAD is assumed to be within a

circle of radius,  $r$ , centered at  $P$ . Therefore, the task is to determine whether the polygon defined by  $v_i$  ( $i = 1 \dots N$ ) intersects this circle and if, therefore, the PAD may be within the polygonal zone. Figure 6 shows a general illustration of this problem. It should be noted that in this figure and throughout this paper,  $v_{i+1}$  is used to indicate the polygon vertex next to the vertex  $v_i$  advancing in a clockwise direction. The  $i+1$  index is used for simplicity in notation, but is not entirely accurate in that the vertex following  $v_N$  should be  $v_1$  and not  $v_{N+1}$ .

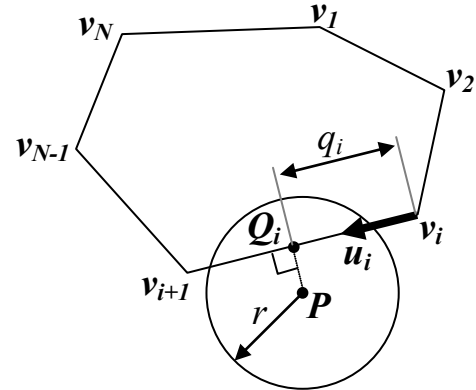


Figure 6 - Zone identification algorithm shown for an arbitrary  $N$ -sided polygonal zone.

The first step is to determine whether  $P$  is within the polygonal zone. This is done by evaluating Equation 1, in which  $\mathbf{u}_z$  is a unit vector in the upward vertical direction, for  $i = 1 \dots N$ . If this expression is true for all values of  $i$ , then  $P$  must be within the zone in question.

$$[(\mathbf{P} - \mathbf{v}_i) \times (\mathbf{v}_{i+1} - \mathbf{v}_i)] \cdot \mathbf{u}_z > 0 \quad (1)$$

If this is not true, the next step is to determine whether the circle intersects any of the polygon edges. Each edge is checked individually. To do this, first a unit vector,  $\mathbf{u}_i$ , is defined pointing from  $v_i$  to  $v_{i+1}$  by Equation 2.

$$\mathbf{u}_i = \frac{\mathbf{v}_{i+1} - \mathbf{v}_i}{\|\mathbf{v}_{i+1} - \mathbf{v}_i\|} \quad (2)$$

This unit vector is used to find a point,  $Q_i$  which is the closest point to  $P$  on the polygon edge. The distance from  $v_i$  to  $Q_i$  is defined as  $q_i$  in Equation 3. This distance,  $q_i$ , is constrained by the expression in Equation 4, and any values falling outside this range are set equal to the limits. The point  $Q_i$  is then defined by Equation 5.

$$q_i = (\mathbf{P} - \mathbf{v}_i) \cdot \mathbf{u}_i \quad (3)$$

$$0 \leq q_i \leq \|\mathbf{v}_{i+1} - \mathbf{v}_i\| \quad (4)$$

$$\mathbf{Q}_i = q_i \mathbf{u}_i + \mathbf{v}_i \quad (5)$$

If Equation 6 is true for any value of  $i$ , the circle centered at  $P$  must intersect the polygonal zone.

$$\|(P - Q_i)\| \leq r \tag{6}$$

Finally, if Equation 1 is true for all values of  $i$  or if Equation 6 is true for any value of  $i$ , the PAD is located within the zone. This condition is expressed in Equation 7.

$$\left. \begin{aligned} &[(P - v_i) \times (v_{i+1} - v_i)] \cdot u_z > 0 \quad \text{for all values of } i \\ &\text{or} \\ &\|(P - Q_i)\| \leq r \quad \text{for any value of } i \end{aligned} \right\} \tag{7}$$

This algorithm is repeated for each zone to determine in which zone(s) the PAD is located.

Once the PAD location and uncertainty are determined, an algorithm to handle hysteresis and noise rejection (such as time averaging, predictive solutions based upon previous location, etc.) may be used to further refine the PAD location and uncertainty value.

### III. MEMS APPLICATION

#### A. State-Of-The-Art in Posture Identification

A previous NIOSH study found that workers' chances of being struck by a CMM are significantly affected by their posture. The investigation found that the relative risk of being struck in a squatting posture to be significantly greater than a standing posture [2]. Figure 7 shown below illustrates the model used of the man/machine interface to determine the risk of an accidental striking. Because of posture's influence on escape ability (Figure 8), the design of the zones in a proximity detection system should account for this important variable. NIOSH is currently investigating methods by which the posture of miners could be identified in real time by a wearable sensor system. This posture data could then be incorporated into the iPDS, and the shape and/or size of the safety zones could be dynamically altered.

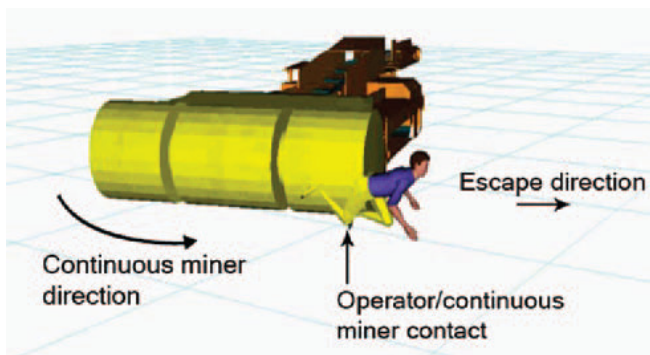


Figure 7 - Simulation snapshot showing the man/machine interface to determine the chance of a striking accident.

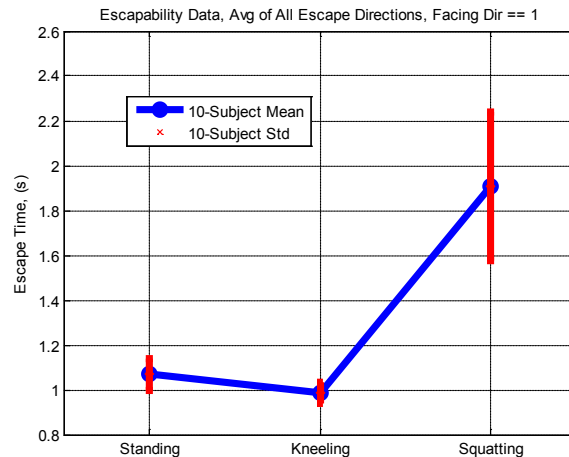


Figure 8 – Mean escape time as a function of posture – squatting results in a 2X increase in escape time.

Posture identification systems are not widely adopted for commercial and industrial applications; however, a great deal of research has been conducted on the measurement of human posture and body orientation. The healthcare industry is rapidly investing in tele-health monitoring. The current desire of patients to have home-based care has led to an increase in the number of posture measurement systems. These units are used to relay objective information about the patients' lifestyle to the caregiver. From the measured data, several key metrics can be calculated which correlate to quality of life including time spent sitting, lying down, energy expenditure and detection of falls. In addition, cell phone-based posture identification systems are beginning to be developed to provide feedback to individuals on their activity levels for fitness monitoring. Researchers at Intel's Seattle complex are working on UbiFIT (Ubiquitous Fitness Influencing Technology) which will incorporate several sensing capabilities including audio, acceleration, barometric pressure, temperature, humidity, compass heading and light level into future cell phones [5]. By developing algorithms to determine physical activity levels from these sensors, the phone could then encourage users to engage in more physical activity and report that information across social networks to bring groups of people together to encourage a more active community.

Current research of posture systems reveals a variety of sensing elements being investigated. The continuing development of microelectromechanical systems (MEMS) has allowed for the development of small-scale, low-cost sensor systems that can be worn by a person. Accelerometers, gyroscopes, variable resistance sensing elements, bend sensors or goniometers, inertial measurement units, global positioning units, microphones, atmospheric pressure sensors, thermocouples, hydrometers, magnetometers, and photometers have all been used either singly or usually as a system to determine posture and activity. It is beyond the scope of

this document to discuss each of these sensing technologies in detail here. Most often these sensors are combined to form a sensor-fusion platform, whereby the measurements of multiple sources are combined to yield a more accurate answer than could have been found by using the sensors singularly. Some common successful combinations have included a height sensing inertial measurement unit (IMU), also known as an altitude heading reference system (AHRS), which combines a MEMS IMU with MEMS pressure sensor [6] and also accelerometers paired with RSSI (received signal strength indicators) [7].

### B. Application to a Specific Posture Identification Problem

The mining environment poses many challenges to delicate sensing equipment – including dust, moisture, and shock exposure. Sensing assemblies for mining use are typically packaged in a robust case that seals them from the environment to prevent damage. Usually these cases have a cost in terms of bulky packaging. Thankfully, the acceptance of MEMS devices has greatly reduced the space occupied by sensors and increased the opportunity for worker-worn sensing equipment. Depending on how it is packaged, a MEMS IMU can survive everything up to and including the ride on the head of a ballistic missile [7]. MEMS inertial units are small, offer decreasing drift rates and are becoming increasingly affordable. The miniature inertial units are completely solid state and contained in sealed enclosures which makes them durable. Because of their shrinking size (Figure 9), it is plausible to have the devices embedded in clothing with minimal discomfort or added weight.

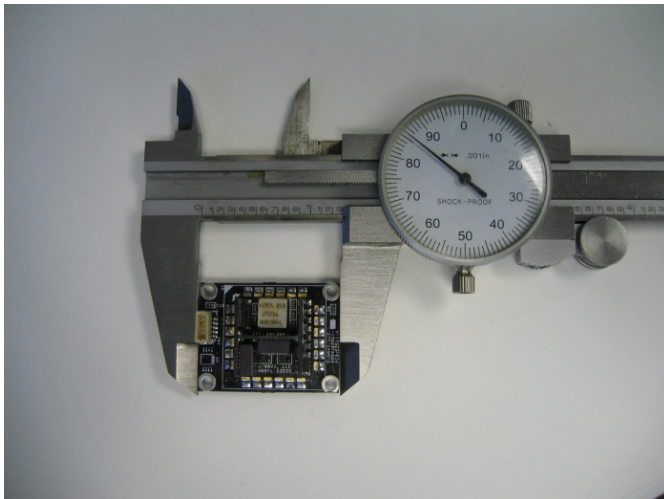


Figure 9 - Example MEMS circuitry showing the footprint size of approximately 33 mm (1.3 in).

A major challenge to the widespread use of MEMS inertial technology is the substantial drift performance. Researchers in Pisa, Italy recently stated that: “One of the most critical aspects connected with the use of inertial motion-sensing is represented by the influence of sensor bias and sensitivity drifts on the accuracy of inertial processing...” the

reconstructed trajectory is unreliable and inaccurate” [8]. As a function of the manufacturing process, MEMS chips are typically tested and then sorted into drift performance ranges. The least expensive sensors, therefore, have the highest drift rates. As MEMS manufacturing technology continues to develop, the sensor performance will increase as the cost goes down, just as it has for the past 15 years.

There are host of posture identification schemes based on the analysis of accelerometer data. One design goal for such a system could be to have a robust hardware answer to the problem instead of a software-centric solution. Relying on advanced algorithms can be problematic when the worker’s behavior is highly dynamic as is the case with the mining environment. Such accelerometer systems have been shown to be very adept at detecting gross postures with large amplitude changes in the signals and less effective with more subtle posture differences which exhibit much smaller signal deltas [9,10].

### C. Collision Avoidance Ramifications

If real-time posture could be calculated, then the detection zones around the machine could be further refined to vary with miners’ posture. While an algorithm could be coded with default values of posture that assume a worst-case scenario for escapability (squatting), this would yield unnecessarily large and cumbersome zone definitions for positions that offered faster egress. The goal of the iPDS is to enable coal miners to work safely close to the continuous miner but prevent machine actions that could endanger them. By contrast, other commercially available systems form a “bubble” around the machine which forces the miner out spatially and into areas where it may be more difficult and potentially unsafe to operate the equipment (unsupported roof, shuttle car dangers, etc).

## IV. DISCUSSION

Research is continuing to improve the performance of this prototype intelligent proximity detection system. This research will also quantify the accuracy and reliability that can be achieved with an iPDS using the zones described in this paper and installed on a working mining machine. Along with some knowledge of the mining environment and processes, this will give a good indication of the expected safety gains provided by this type of system. The researchers plan to incorporate posture identification into the iPDS control methodology and investigate the usability of this technology and its acceptance by continuous mining machine operators. An educational campaign is under development that will promote this acceptance.

## V. 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.

## VI. ACKNOWLEDGEMENTS

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