

Development of a Method to Determine Operator Location using Electromagnetic Proximity Detection

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Abstract— Researchers at the National Institute for Occupational Safety and Health (NIOSH) are advancing the emerging technology of electromagnetic proximity detection, which provides a promising means of protecting workers around any machinery that presents striking, pinning or entanglement hazards. This technology is particularly applicable to mobile underground mining equipment such as remote-control continuous mining machines, which offer perhaps the most difficult safety challenges in the mining industry. Other industries have effectively implemented proximity detection technology, with successful test cases at surface and underground mines. However, applying this technology to remote-control continuous mining machines presents uniquely difficult challenges. These machines typically weigh close to 100,000 pounds and have heavy, articulated parts. Due to visibility and space limitations, machine operators often work in very close proximity to the machine despite the clear hazards that this proximity creates. To protect miners without preventing them from doing their jobs or causing nuisance alarms, intelligent electromagnetic proximity detection technology is now being developed at the NIOSH research facility in Pittsburgh. At the heart of this technology are a number of electromagnetic field generators mounted on a mining machine and magnetic flux density sensors built into a Personal Alarm Device (PAD) worn by the operator. In this paper, the authors present a novel algorithm created to calculate an accurate position based on PAD readings from multiple field generators coupled with a previously developed model of the generated magnetic field. The use of this algorithm allows for the calculation of an accurate PAD location relative to the mining machine. A prototype of this intelligent proximity detection system has been successfully implemented and demonstrated on a Joy 14CM continuous mining machine at the NIOSH research facility in Pittsburgh. This technology has the potential to significantly affect the mining industry by greatly advancing the current state-of-the-art in proximity detection technology, leading to increased operator safety and preventing serious injuries and fatalities.

Keywords—coal mining, proximity detection, traumatic injuries, striking/pinning

1. INTRODUCTION

Underground coal mining in the United States commonly uses mechanical excavation methods with machines such as continuous mining machines like the one shown in Fig. 1. To protect the operator from potentially dangerous areas of the mine where there may be unsupported roof, these machines are

typically operated via remote control. While this protects the operator from certain hazards, it also creates the potential for other hazardous situations to occur. According to the Mine Safety and Health Administration (MSHA), during the period of 1999 to 2006 in the United States, there were, on average, 254 accidents per year during routine mining activities involving remote-control continuous mining machines. Further, since 1984, there have been 33 fatalities in which workers were struck by or pinned by these machines. The working environment in underground coal mines is often harsh as represented in Fig. 2. Confined spaces, low roof heights and wet or muddy conditions limit the mobility of people. Poor illumination, high levels of glare, and dust in the air greatly reduce visibility, and high levels of noise hinder communication between workers. The presence of large pieces of moving equipment in this environment creates safety hazards unique to underground mining. MSHA recommends that miners avoid "red zones" that define dangerous areas around the machine. Training campaigns inform mine workers of the red zones and how to avoid them. While red zones provide good guidance to miners and can prevent many accidents through behavioral change, they are not a foolproof safeguard.

To better guarantee that workers stay out of dangerous areas, and to ensure that the machine does not make dangerous motions while people are in close proximity, a technological



Figure 1. A continuous mining machine.

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Figure 2. Typical underground coal mine working environment.

control is needed. A promising technology is electromagnetic proximity detection, which utilizes magnetic fields to determine the proximity of workers to the machine. Software for this technology is crucial for determining position from magnetic field readings. This paper presents a novel and efficient method for determining position of a worker in two- or three-dimensional space around a mobile machine. This method will greatly improve the safety of miners while also reducing the frequency of nuisance alarms that are a problem for some proximity detection systems.

II. BACKGROUND

A. Proximity Detection

Several types of proximity detection systems using various technologies have been developed [1]. Some of the technologies utilized in surface mining and in other industries include the Global Positioning System (GPS), radar, and laser- or ultrasonic-based distance sensors. Unfortunately, these technologies are mostly ineffective in underground mines, where GPS is unavailable due to line-of-sight constraints, and the constant close proximity of mine walls makes the use of the other technologies extremely difficult.

Another possible solution is the use of Radio Frequency Identification (RFID) technology. Many industries commonly use RFID for tracking the movement of 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. RFID 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 they are currently ineffective at providing an accurate distance reading from the transmitter. RFID is, therefore, not currently suitable for determining the position of a person near a moving machine.

Yet another emerging technology is intelligent video systems utilizing complex algorithms to identify and locate people and objects within a visual scene. Application of this technology in the underground mining industry, however, is likely to be very challenging due to poor lighting, dust and the extreme difficulty in keeping the cameras clean.

To overcome these challenges, tag-based electromagnetic proximity detection technology was developed at the National

Institute for Occupational Safety and Health (NIOSH) about 10 years ago [2]. This technology was proven to be an effective means of providing a reasonable estimate of the distance between a person and a machine. Electromagnetic proximity detection systems use an electromagnetic field generator to create a magnetic field that is measured by a sensor. The generator is mounted on the machine and the sensor is placed in a wearable Personal Alarm Device (PAD). The magnetic flux density measured by the PAD increases with increasing proximity to the generator, and thus an estimate of the distance can be made. Since the magnetic flux density measured by a sensor depends on the orientation of the receiver antenna, the PAD typically includes three orthogonal antennae to minimize the impact of PAD orientation. An onboard controller uses this information to issue visible or audible warnings or disable machine movement. This technology is currently being trialed in the United States by mining companies and regulatory agencies.

In the case of remote control continuous mining machines, it is common practice for people to work in very close proximity to the machine to complete their jobs effectively. In fact, it is common for an operator to be located within 1 meter of the machine. This close proximity is desired in order for the operator to see certain visual cues to operate the machine [3]. In order to be acceptable to the miners and to avoid attempts to disable or circumvent the safety device, the proximity detection system must provide the necessary protection while minimizing the occurrence of nuisance alarms. This can be accomplished through the implementation of an intelligent system that can make decisions based on the position of the operator.

B. Preliminary Work in the Development of an Intelligent Proximity Detection System

An intelligent system is needed that can determine the two- or three-dimensional position of the operator relative to the machine and selectively disable only specific machine functions accordingly. For example, if the operator is standing behind the machine, there is no safety concern in allowing the machine to move forward, regardless of how close the operator is to the back of the machine. If, however, the operator attempts to move the machine in reverse while standing close to the rear bumper, an intelligent proximity system would prevent this command from executing.

An intelligent system of this sort requires a method for accurate position calculation. Therefore, an accurate mathematical model of the magnetic field shape is needed. NIOSH researchers have developed such a model for magnetic field generators that use an antenna with a ferrite rod core typical of proximity detection systems [4]. The shape of the magnetic fields is very complex and irregular. Equation (1) defines the shape of the magnetic "shell" in polar coordinates as all points having the same magnetic flux density.

$$\rho = a \cdot \cos(2\theta) + b \quad (1)$$

In this equation, ρ is the radial coordinate measured from the center of the magnetic field generator and θ is the angular coordinate measured from the long axis of the magnetic field generator. The coefficients a and b are functions of the magnetic flux density as defined in (2) and (3).

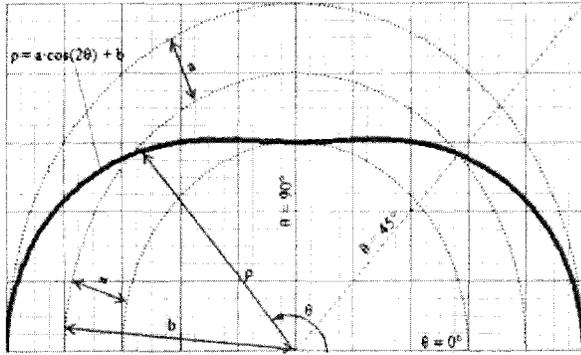


Figure 3. Example magnetic shell described by the model.

$$a = c_a \cdot m^{-d_a} \quad (2)$$

$$b = c_b \cdot m^{-d_b} \quad (3)$$

In these equations, m is the magnetic flux density, which decreases with increasing distance from the magnetic field generator, and c_a , d_a , c_b and d_b are all positive constants dependent on the physical and electrical properties of the generator. These constants must be determined through a calibration process for each generator.

Fig. 3 shows an example of a magnetic shell shape described by (1). This shell represents all points at which a constant magnetic flux density is measured. Notice that the shell radius varies between $(b+a)$ at $\theta = 0^\circ$ and 180° and $(b-a)$ at 90° . The shell intersects a circle of radius b at 45° and 135° . Inspection of (1) shows that this radius variation will always be the case. It should be clear from examination of Fig. 3 that if the value of a is large in relation to b then the shape of the magnetic shell will be more irregular. However, if a is very small in relation to b , the shape of the shell will become more regular, approximating a circle. Referring to (2) and (3), the constants behave in such a way that $0 < c_a < c_b$ and that $0 < d_a < d_b < 1$. This means that as the magnetic flux density, m , becomes smaller (i.e. the distance from the generator becomes larger), both a and b will increase, but the rate of increase for b will be much faster. Therefore, as the distance from the generator increases, the shapes of the magnetic shells become more regular. This phenomenon is shown in three dimensions in Fig. 4. The three-dimensional model is found by the fact that the magnetic field is rotationally symmetric around the $\theta = 0^\circ$ axis.

III. POSITION DETERMINATION

The position of the PAD is determined by finding the intersection of two or more magnetic shells. Due to the irregular shapes of these shells, determining this intersection is not a trivial task, and an analytic solution cannot be determined. While numerical techniques such as Newton's Method and the Monte-Carlo Method 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 iteratively converges on the intersection of two shells in either two or three dimensions. The major benefit of this method is that it does not require significantly more

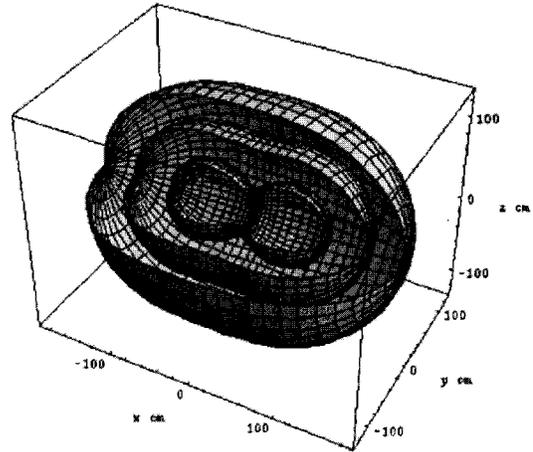


Figure 4. Example of the variation in the magnetic shell shape with increasing distance from the generator.

computation to find solutions in three dimensions. This makes it feasible for use with an onboard controller.

This method converges to the intersection of the shells through an iterative series of spherical approximations. This method can most easily be visualized in a two-dimensional simplification as shown in Fig. 5. In this figure, two generators, 0 and 1, are located in a plane at arbitrary positions, \bar{P}_0 and \bar{P}_1 , and arbitrary orientations. The solid lines around the generators indicate the magnetic shells defined by (1) in which the angles θ_0 and θ_1 are defined relative to the long axis of generators 0 and 1, respectively. The shells can be approximated by two circles of radius r_0 and r_1 . For the first iteration, an initial guess for the radii is made by assuming the average shell radius b as defined in (3). These two circles will intersect at up to two points, \bar{I}_0 and \bar{I}_1 . From either of these intersections, the angles θ_0 and θ_1 can be determined through geometry. These angles can then be used with (1) to determine the model shell radii, ρ_0 and ρ_1 . These radii are then used as the new radii, r_0 and r_1 , of the circular shell approximations, and the process is repeated. It has been empirically determined that if this process is iterated, and the intersection \bar{I}_0 is used in every iteration, the solution will quickly converge to the actual intersection, \bar{I}_0^* , of the two

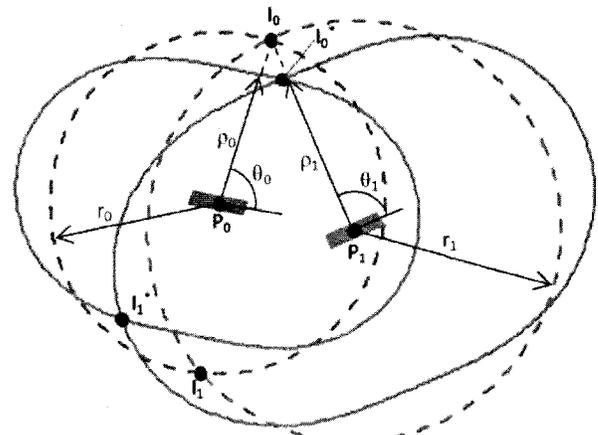


Figure 5. Spherical approximation method represented in 2 dimensions.

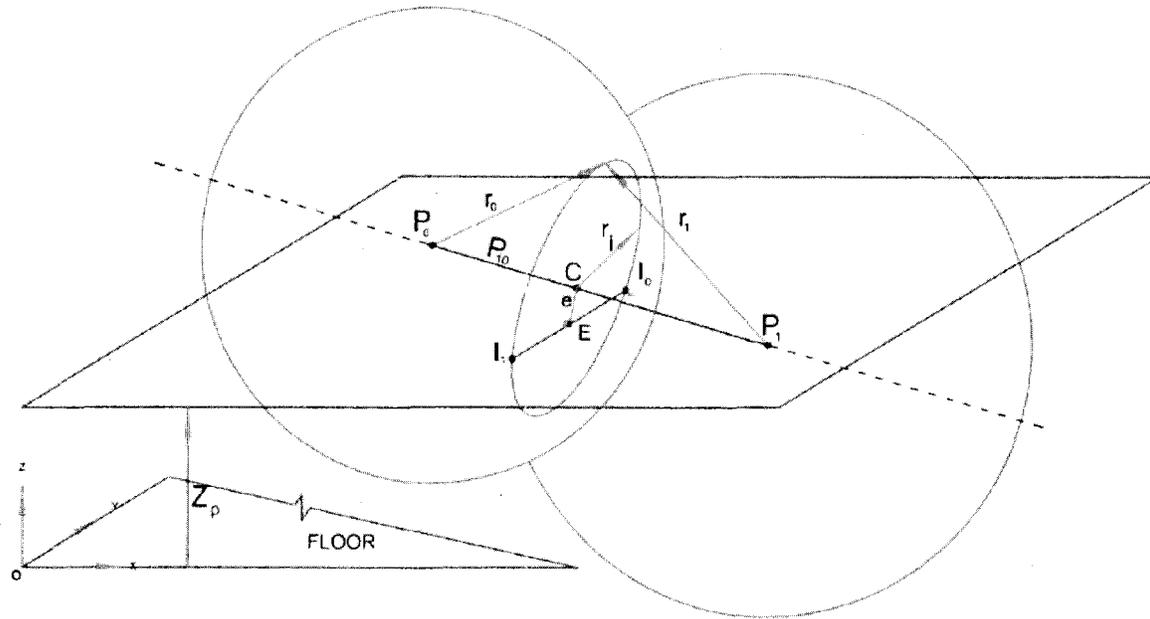


Figure 6. Vector analysis for spherical approximation method.

shells. Similarly, if \bar{I}_1 is used, \bar{I}_1^* will be found. Iteration of the algorithm is stopped when the radii, r_0 and r_1 , change by an amount less than a preset tolerance.

To extend this algorithm to three dimensions, the three-dimensional shells are approximated with spheres, and some additional constraining assumptions are made. It should be clear that an intersection between two three-dimensional shells would be either a point or, more likely, an infinite number of points located on an intersection curve. Therefore, to limit the possible number of solutions, a further assumption is made that the PAD lies in a plane assumed parallel to and at a specified waist height from the ground surface. This assumption should introduce only minimal inaccuracy into a proximity detection system. Based on the posture of the miner, a reasonably accurate assumption about the PAD elevation can be made, and due to the relatively gentle vertical curvature of the shells, an error in the assumed PAD elevation should result in only a small error for the calculated PAD position.

A method to calculate the intersections of two spheres with an assumed horizontal plane is therefore needed. This would yield a) no solutions, should the surfaces not meet; b) one solution if the spheres meet at a single point which also lies in the assumed PAD plane or if the intersection circle between the two spheres touches the assumed PAD plane in a single point - both of which are mathematically highly unlikely; c) two solutions where the intersection circle intersects the assumed PAD plane; or d) an infinite number of solutions if the intersection circle lies in the assumed PAD plane - highly unlikely due to generator locations relative to the assumed plane. Therefore, case (c) in which two solutions exist is most likely to occur and is of primary interest in the development of this algorithm.

A straightforward vector analysis is utilized for the algorithm. Fig. 6 and Fig. 7 show the vectors used to solve for

the intersections of a generic case of two spheres of arbitrary location and the assumed plane in which the PAD lies. The solution method is as follows:

Define a reference frame relative to the machine on which the generators are mounted. In this frame, the Z axis will be orthogonal to the ground surface on which the machine is sitting. All vectors defined in the following equations are defined in this frame. Let \bar{P}_0 and \bar{P}_1 be the vectors identifying the positions of generators 0 and 1 as well as the centers of the corresponding spheres 0 and 1; z_p the assumed height of the

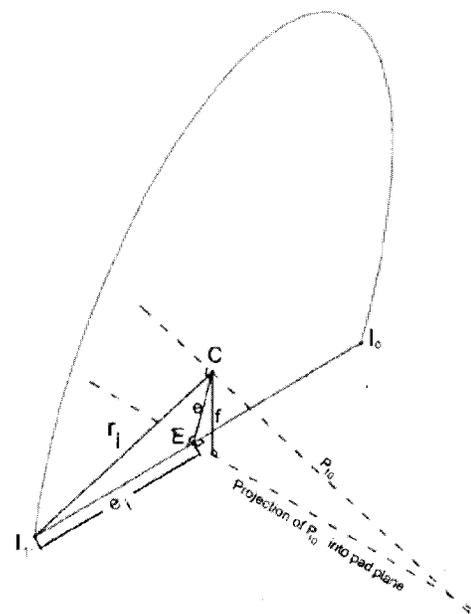


Figure 7. Detail of vector analysis for spherical approximation method.

PAD from the floor; and r_0 and r_1 the radii of spheres 0 and 1.

The first step in determining the intersection points is to determine the center of the intersection circle between the approximating spheres. \bar{P}_{10} is the vector pointing from the center of sphere 0 to the center of sphere 1 (4) whose magnitude is p_{10} (5) and unit vector is \bar{P}_{10} (6). The scalar quantity p_{c0} is determined by geometry as the magnitude of the vector from the center of sphere 0 to the center of the intersection circle, C (7), and used to create the associated vector \bar{P}_{c0} (8), which in turn is used to determine the position vector, \bar{P}_c , for the center of the intersection circle (9).

$$\bar{P}_{10} = \bar{P}_1 - \bar{P}_0 \quad (4)$$

$$p_{10} = |\bar{P}_{10}| \quad (5)$$

$$\bar{P}_{10} = \bar{P}_{10}/p_{10} \quad (6)$$

$$p_{c0} = (p_{10}^2 - r_1^2 + r_0^2)/(2p_{10}) \quad (7)$$

$$\bar{P}_{c0} = p_{c0}\bar{P}_{10} \quad (8)$$

$$\bar{P}_c = \bar{P}_0 + \bar{P}_{c0} \quad (9)$$

The next step is to determine the center of the chord of the intersection circle that lies in the assumed PAD plane and contains the two possible solution points. The radius, r_i , of the intersection circle is calculated for later use (10). The scalar f is the magnitude of the perpendicular distance from the assumed plane to the center of the intersection circle (11). The first cross-product of the vertical unit vector, \hat{k} , with the unit vector, \bar{P}_{10} , produces a unit vector, \hat{I}_0 , perpendicular to the plane containing \bar{P}_{10} and \hat{k} (12). The second cross-product produces a unit vector, \hat{E} , pointing from the center of the intersection circle, C, to the center of the intersection chord, E (13). The scalar value e is found as the distance from the center of the intersection circle, C, to the center of the intersection chord, E, (14) and is used to construct \bar{E} (15) which is, in turn, used to determine the position of the center of the intersection chord, \bar{P}_E (16).

$$r_i = \sqrt{r_0^2 - p_{c0}^2} \quad (10)$$

$$f = \bar{P}_c \cdot \hat{k} - z_p \quad (11)$$

$$\hat{I}_0 = \hat{k} \times \bar{P}_{10} \quad (12)$$

$$\hat{E} = \hat{I}_0 \times \bar{P}_{10} \quad (13)$$

$$e = f/(\hat{k} \times \bar{E}) \quad (14)$$

$$\bar{E} = e\hat{E} \quad (15)$$

$$\bar{P}_E = \bar{P}_c + \bar{E} \quad (16)$$

The final step is to determine the location of the intersection points. The scalar e_i is geometrically determined (17) to be the distance from the center of the intersection chord, E, to either intersection. The positions of the intersections, \bar{I}_0 (18) and \bar{I}_1 (19), can then be determined using the magnitude, e_i , and the direction unit vector, \hat{I}_0 , perpendicular to the plane containing \bar{P}_{10} and \bar{E} .

$$e_i = \sqrt{r_i^2 - e^2} \quad (17)$$

$$\bar{I}_0 = \bar{P}_E + e_i\hat{I}_0 \quad (18)$$

$$\bar{I}_1 = \bar{P}_E - e_i\hat{I}_0 \quad (19)$$

These solutions can then be used for successive iterations as described for the two-dimensional case to converge to the actual intersections of the shells. This method converges to the PAD position in typically fewer than 15 iterations.

IV. SIMULATION TRIALS

The efficiency, accuracy and stability of the developed methods have been tested extensively in simulation. In these simulations, the magnetic field model is calibrated to the output of a commercially available proximity detection system used in the laboratory trials.

Fig. 8 shows an example of the results of these simulations. In this example, two generators with slightly different model constants were placed 200 cm apart and the location of all points within a 10-m by 5-m grid with 5-cm resolution were triangulated. Nearly all points on this grid converged to within a tolerance of 0.1 cm in less than 15 iterations. The asymmetry seen in this figure is due to the two generators having slightly different calibration. There are locations in which the method does not converge to a solution; notably, any point that is collinear with the generators will not converge. However, if three or more generators are used, it will be very unlikely that none of the generator pairs would converge to a solution. Therefore, the system should practically always converge to a position solution.

V. LABORATORY TRIALS

A. Trials using Laboratory Hardware

The methods developed for determining the position of a PAD were tested in the laboratory using a custom-made system. In these tests, precisely machined ferrite-cored antennae powered by a laboratory signal generator and amplifier generated the magnetic fields, and a laboratory grade magnetic sensor replaced the PAD.

Using the information from two alternately pulsed generators located in a two-dimensional system spaced one meter apart, the position of each of 40 points in an area of 1.0 meter x 0.9 meter was determined as the intersection of the two field shells. For these 40 points, the mean location calculation error was 6.61 mm, the standard deviation of the error was 2.25

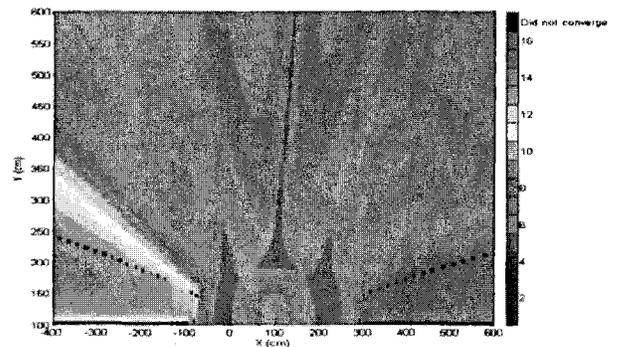


Figure 8. Number of iterations required in simulation for the spherical approximation method to converge to within a tolerance of 0.1 cm.

mm, and the maximum error was 11.67 mm.

B. Trials using Commercially Available Hardware

Following testing with laboratory equipment, tests were performed using commercially available proximity detection hardware. Fig. 9 shows an example of the results of these tests. Testing was conducted with a number of generator positions and orientations. In this example, two generators were placed 200 cm apart and oriented 90 degrees to the line between them. The PAD was positioned at all points on a 240-cm by 120-cm grid with 20-cm spacing. The laboratory trials using the commercially available hardware showed that the method was feasible with this hardware. However, the errors seen were much larger than for the laboratory hardware, with errors of up to 20 cm being seen.

During testing, a number of design and manufacturing flaws in the commercially available hardware were noticed. These flaws include the fact that the three sensor coils in the PAD were placed too far apart causing inconsistent field readings, the sensor coils were not mounted exactly orthogonally, and compensation for field distortion was not implemented. Design flaws also exist in the generators, which include the power amplifier in the same enclosure causing distortion of the field.

While correcting these flaws would surely improve the accuracy of the system, the authors do not consider the magnitude of error observed to be prohibitive to the implementation of this method in a proximity detection system. Previous NIOSH research used simulations to determine the factors that most significantly influence struck-by accidents involving continuous mining machines [5]. These simulations employed digital human models based on motion capture data of experienced machine operators. The results of this study indicated that, regardless of machine speed, the probability of struck-by accidents involving continuous mining machines drastically decreases if miners are at a distance of at least 1 meter from the machine. With this in mind, if a system were designed with appropriate safety factors, the accuracy observed in the laboratory trials would allow for proper decisions about safety status and would provide the information needed to significantly improve miner safety.

VI. DISCUSSION AND FUTURE WORK

The triangulation algorithms that have been developed make 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 represents a significant advance in the technology of proximity detection and is expected to greatly improve the safety of underground coal miners.

These algorithms are now being implemented in a prototype intelligent proximity detection system on a Joy 14CM continuous mining machine at the NIOSH research facility in Pittsburgh. This prototype system will demonstrate the capability of the algorithms described in this paper to accurately determine the two- or three-dimensional position of a person near the machine and respond intelligently by issuing alarms or preventing machine functions that would cause an accident. One of the major obstacles to implementing this

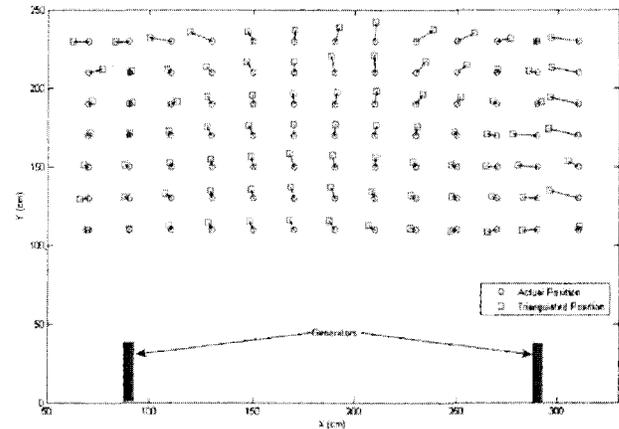


Figure 9. Example results of laboratory trials using commercially available proximity detection hardware.

prototype system is the fact that the magnetic fields used are affected by being mounted on a large metal machine. However, with proper calibration, this impact can be taken into account and should not significantly affect the system's performance.

Research is continuing to improve the performance of this prototype system. This research will also quantify the accuracy and reliability that can be achieved with an intelligent proximity detection system using the algorithms 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 that this type of system will provide. The researchers also plan to 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. NIOSH plans to complete this research by the end of the year 2011 and will make this new technology available to the mining industry as the research is completed.

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