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ANALYSIS, CONVERSION, AND VISUALIZATION OF SURVEY POSITION AND MAGNETIC FLUX DENSITY DATA FOR A PROXIMITY DETECTION SYSTEM

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ABSTRACT

Underground continuous mining machines pose a difficult safety challenge since their operators generally work in close proximity to these machines in very restricted spaces. Intelligent software for use with magnetic proximity detection systems has been shown to accurately locate workers around mining machinery in real time. Calibrating these systems requires the manipulation of a lot of data to determine the calibration constants. Researchers have developed software to analyze, convert, and visualize data acquired during this calibration process to more accurately model magnetic fields and their interaction with the environment. This paper details the background, development, and operation of the resulting application software focusing on the utility of the graphical user interface to visualize the magnetic field calibration data. The refined data developed by this process can then be utilized by the proximity detection system to more accurately identify the location of miners working in an underground mining environment.

INTRODUCTION

Roughly half of the electricity consumed in the United States is produced with coal, and roughly one-third of all US coal production comes from underground mines [1]. Over the last century underground mining health and safety has seen a continuous and dramatic improvement. However, machine-related injuries and fatalities continue to be a major safety concern [2].

Every year, hundreds of miners are severely injured while operating underground mining equipment, and 39 miners have been killed in striking/pinning accidents involving continuous mining machines (CMMs) since 1984. CMMs, such as the one shown in Figure 1, are large mobile machines that are used to mechanically cut coal in an underground mine. These machines weigh approximately 40 to 50 tons, have hydraulically articulated appendages, and are capable of moving at speeds up to six feet per second [3]. Modern CMMs are remote-controlled, yet the operator and other miners are often in close proximity to the machine. Recent research by the National Institute for Occupational Safety and Health (NIOSH) reveals that the locations workers take relative to the CMM are usually influenced by visibility requirements and safety concerns [4]. The Mine Safety and Health Administration (MSHA) estimates that at least 28 fatalities involving CMMs since October of 1984 may have been prevented with proximity detection technology [5]. MSHA further estimates that proximity detection could prevent 20% of all deaths throughout the industry [6].

Current CMM proximity detection systems are based on past NIOSH research that investigated the use of low- frequency magnetic field generators mounted on the machine [7]. A receiver worn by personnel working in the vicinity of the CMM detects the generated magnetic flux density. Based on the measured flux density, the proximity detection system estimates the distance of personnel to the machine. These systems produce audible and visible notifications and are also capable of disabling a CMM's motion when a miner is detected in hazardous proximity to the CMM.

Figure 1. Continuous mining machine underground.

In January 2015, MSHA published the final regulation that would require the use of proximity detection systems on all CMMs except full-face machines [8], and has approved three such systems for use in underground coal mines. NIOSH researchers have conducted a series of performance tests on systems deployed underground [9], and results suggest that this technology can significantly improve safety. However, testing also revealed opportunities for improvement, such as refinements embodied in the NIOSH-developed Intelligent Proximity Detection (iPD) System [10, 11]. This paper details the background, development, and operation of the resulting application software focusing on the utility of the Graphical User Interface (GUI) to visualize the magnetic field calibration data.

DEVELOPMENT OF INTELLIGENT PROXIMITY DETECTION

Magnetic Field Modeling

Recently, NIOSH researchers developed the iPD system, which is designed to provide more efficient protection by disabling only the motions that would present a CMM striking or pinning hazard [11]. By blocking only potentially hazardous actions, safe mining activities are allowed to continue uninterrupted. It is expected that this approach will increase operator acceptance of proximity detection systems [12].

The iPD system continuously tracks the position of all miners wearing Personal Wearable Devices (PWDs) near the mining machine. The system employs NIOSH- developed methods to model the shapes of the magnetic fields [13, 14], to track the position of the miners relative to the machine [15], and to detect safety zone intrusions [16]. These methods rely on a mathematical model which describes the shapes of magnetic "shells," which are defined by points having equal magnetic flux density. An example of the three-dimensional variation in shape and size of magnetic field "shells" within an equal-permeability medium around a single PD system generator is shown in Figure 2, where the generator is at the center of the coordinate system.

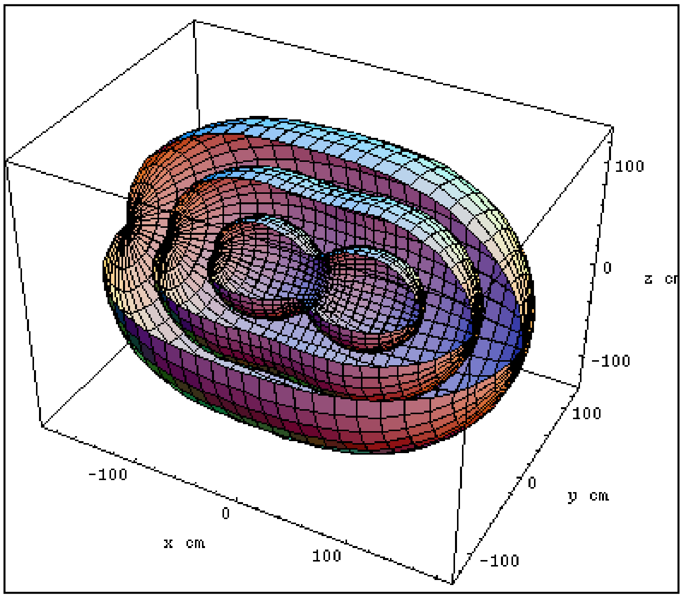

Figure 2. Example of the variation in magnetic shell shape with increasing distance from the generator.

Determining Miner Position

Given this model of the magnetic fields, a novel method was developed for determining the location of a 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 to be impractical 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 [15].

Intelligent Proximity Detection with Permissible Hardware

A commercially available permissible proximity detection system was modified 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. One of the machine mounted generators is shown in Figure 3, along with the location of the controller. Figure 4 shows the PWD and a robotic total station target prism mounted on the data collection pole. Each of the 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 adjusted for optimum range.

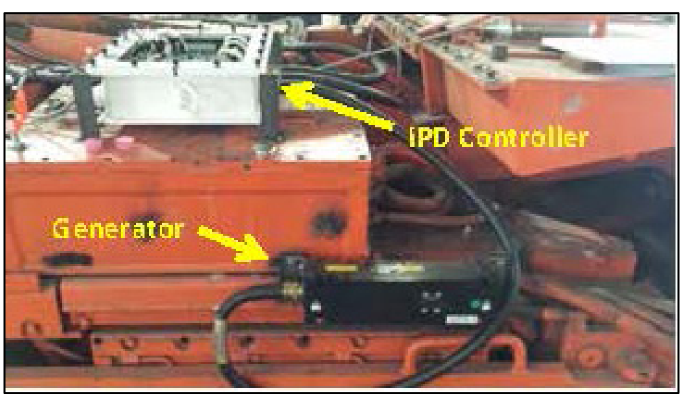

Figure 3. Permissible proximity detection system controller and magnetic field generator.

Figure 4. Personal wearable devices mounted on data collection pole.

iPD SYSTEM OPERATION DATA COLLECTION

To map the magnetic flux density and shapes for each field generator and the sensitivity of each PWD, a grid was laid out around an iPD-equipped CMM. To accurately determine and log the location of the PWDs and iPD system generators on the CMM, a robotic total station was employed. Figure 5 shows the general layout as seen from the robotic total station location. Reflective targets permanently affixed in the test area allowed for the precise referencing of the robotic total station's location, while target prisms served as location control points on the CMM and data collection pole used to support PWDs. Reflective targets mounted on the iPD field generators (seen in Figure 3) allowed for determining their precise location and orientation on the CMM. A device mounted to the top of the data collection pole allowed the robotic total station to automatically track the pole while the station's field controller was used to log its location during testing.

An application was written to interface with the iPD system to collect the raw field measurement data being returned for each of the three axes from each of the three PWDs (shown in use in Figure 6) at each of the 487 data collection grid locations in the test area. One hundred readings from the iPD system and the surveyed location of the data collection pole were collected at each grid point.

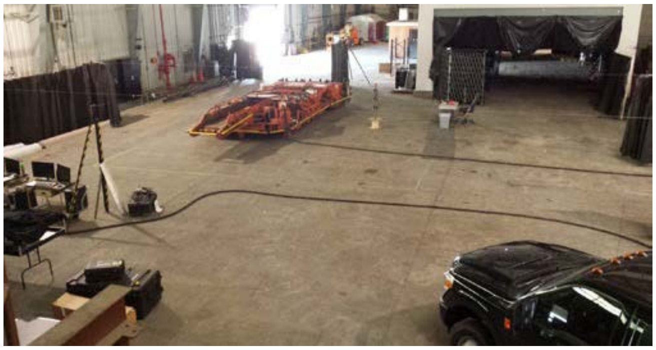

Figure 5. Test area as seen from robotic total station.

Figure 6. Data collection test bed.

DATA ANALYSIS AND MAPPING APPLICATION DEVELOPMENT

Software Architecture

A MATLAB application was written to facilitate the analysis, conversion and visualization of the large amounts of data to be processed. Several distinct functions were performed by the software. The first was to convert all of the survey data points into a common reference frame. This conversion was necessary due to the fact that there were several separate coordinate reference frames used: 1) for the location and orientation of the CMM in the test area, 2) the location of each test point, and 3) the locations of the generators on the CMM. This process relied heavily on well-established matrix methods and coordinate transformation techniques. Once all of the points contained in the survey data sets were in the same coordinate reference frame, the distance and angles to each PWD from each generator could be calculated for later use. The next function was to read all of the magnetic measurement data points and remove all of those points that showed evidence of saturation in any axis since the results would not be accurate.

Once completed, the axes results were combined into the vector sum number or the magnitude of magnetic flux density that the iPD system uses. Finally, a regular interpolated 10-cm grid (using either linear or cubic spline interpolation) was mapped from the surveyed locations and magnetic flux density magnitudes. This map was then used to generate a more accurate model of the iPD system as installed.

GUI display

To help visualize the results, a GUI was created for the MATLAB application described above. With it, data from each individual generator/PWD combination could be inspected at each data collection point. Also, the GUI allowed for quick changes to be made to the visual representations of the data selected in a more intuitive manner.

Just by examination of the data, it is hard to visualize the effects that the proximity of the CMM has on the generated fields. By displaying shell contour lines representing the flux density magnitude, it was noted that the field tends to bend in towards the CMM corners. This is an expected behavior of magnetic fields, but the ability to quantify the actual effect allows for a better model of the fields to be constructed. Also, a surface can be generated that represents the difference between the modeled location and the actual location based upon the field measurements of each generator reported by a particular PWD. This representation reveals how susceptible the model is to variations in the PWD readings. This allows for a confidence to be assigned to the calculated location.

The GUI has many specialized tools and functions required to support this analysis. It can quickly generate contours and surfaces from the processed data maps, and provides tools that allow zoom, pan, drag and rotation of 3D plots. Color contour maps are also used to represent magnetic flux density within the program.

DISCUSSION

Objects within the GUI were selectable for visualization. Figure 7 shows the numbered data points, the mining machine outline, the location of the machine control points, and the location of the generators. Selecting a particular data point opens a window that displays information pertaining to that data point (PWD height, survey point number, location, direction and distance to PWD from generator, and the flux density magnitude) as shown.

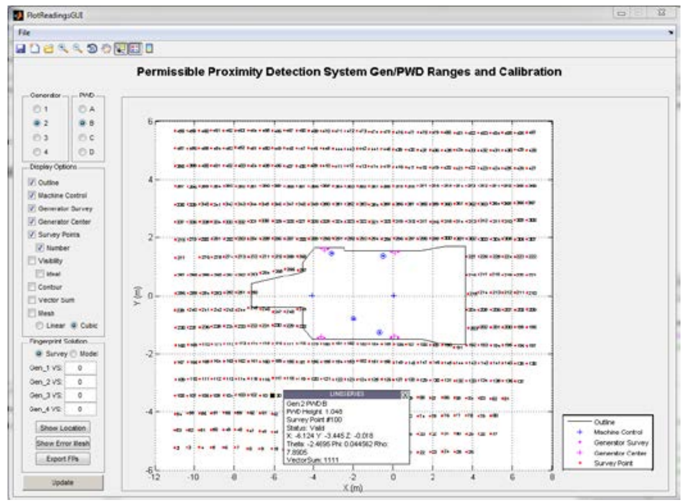

Figure 7. Survey Points with a data inspection window open.

The flux density magnitude contours are shown around a generator mounted on the CMM in Figure 8. Figure 9 shows the superimposed 3D surface displayed from the actual surveyed results. It could also display the model created to best fit the data based upon previous modeling work. The actual magnitude at each survey point can also be superimposed upon the model's 3D surface to see how well it approximates the actual data.

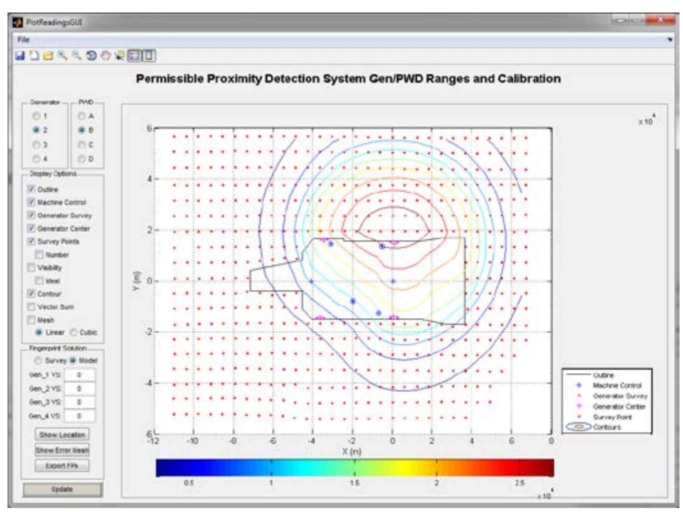

Figure 8. Shell contours for model data from generator 2 magnetic field read by PWD B.

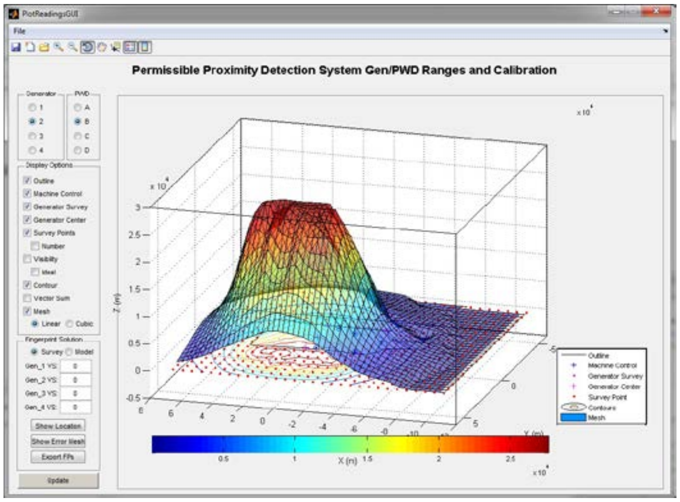

Figure 9. Shell contour and mesh for survey data from generator 2 magnetic field read by PWD B.

Finally, to test the solution method, a GUI option was added to allow for the input of simulated generator flux density magnitude data and the PWD location to be displayed as a red dot near the intersection of the generator magnetic flux density contours. An example of this analysis is shown in Figure 10 with an error surface mesh superimposed to reveal whether the method is susceptible to noisy data.

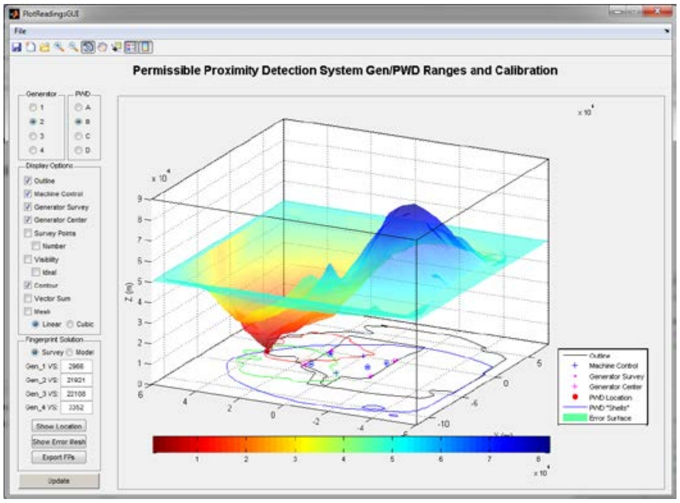

Figure 10. PWD location with generator shell contours and next neighbor error surface.

CONCLUSION

The software described allowed a more efficient and visual method of determining the iPD parameters than previous methods allowed. Being able to inspect the individual data points, display the data in a variety of ways, and visualize the field measurement data as surfaces helped to generate parameters for a better fitting model.

Using this adjusted model, the iPD system has been observed to have improved accuracy in operation at the NIOSH laboratory. Exact quantification of this improvement and a method to envision it needs to be further investigated.

Intelligent proximity technology will provide enhanced safety to CMM operators and will help prevent striking and pinning accidents. Proper application of this technology to underground mobile haulage and utility equipment may also provide similar benefits.

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) 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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