ADVANCES IN PROXIMITY DETECTION TECHNOLOGIES FOR SURFACE MINING EQUIPMENT

Todd M. Ruff, P.E.
Electrical Engineer
National Institute for Occupational Safety and Health

INTRODUCTION

The lack of visibility near earthmoving equipment resulted in six fatalities in U.S. surface mining operations during 2003. These accidents were the result of either a piece of equipment striking another vehicle or worker, or the equipment traveling over the edge of an embankment. Figure 1 is an example of a recent accident that resulted in serious injuries to one worker and fatal injuries to two others when a van parked in front of a haul truck. Two fatalities occurred in separate incidents when front-end loaders struck workers. Another two workers were killed when their equipment backed over the edge of a highwall or dump point [1]. There is clearly a need to provide better information to equipment operators regarding their surroundings.

Figure 1. Accident involving collision between off-highway dump truck and van.

Researchers at the National Institute for Occupational Safety and Health (NIOSH), Spokane Research Laboratory, are working to reduce these accidents by developing systems that sense obstacles and changes in terrain near the equipment and provide this information to the operator. Many off-the-shelf proximity warning systems that were developed for automobiles, light trucks, and recreational vehicles were evaluated on off-highway dump trucks [2]. Many limitations were found with existing systems, including frequent false alarms, limited detection range, a lack of specific information on an obstacle (e.g., location, identity), difficulties in finding suitable mounting locations, and an inability to withstand the environment. These limitations have necessitated the development of new systems designed specifically for large, off-highway, earthmoving equipment. New off-the-shelf systems available for mining equipment include radar and tag-based detection systems. Prototype systems now being developed include a proximity warning system based on the Global Positioning System (GPS) and a computer-assisted stereovision system. Development of these new systems was accomplished by working with manufacturers to modify existing systems to meet the needs of surface mining and through cooperative research with organizations to develop completely new solutions.

A typical proximity warning system consists of a sensor or antenna mounted on the equipment that detects the presence of obstacles and an alarm interface in the cab of the equipment. Some systems, as described in more detail below, also require that other vehicles and personnel on the ground be outfitted with electronic tags that transmit an “I’m here” signal back to the system (e.g., radio signal detection systems or GPS). Many types of proximity warning systems are on the market, but they are not all discussed in this paper.

APPROACH

In past work, engineers at NIOSH evaluated several off-the-shelf proximity warning technologies in order to verify their effectiveness on off-highway dump trucks [2]. Dump trucks were chosen because of the number and severity of accidents involving this type of equipment and because extensive blind areas around these trucks are typical. This experience allowed engineers to limit the number of systems chosen for long-term tests at mine sites to those systems showing the best potential for success. Even so, field tests quickly revealed shortcomings, and work with manufacturers was initiated to modify the systems. At the same time, new technologies were investigated to meet the specific requirements of surface mining equipment and mine environments.

Initial tests were conducted using a 50-ton-capacity, off-highway dump truck. It was critical to test each system on an actual piece of equipment because of the variability seen in performance depending on where the system was mounted on the truck and the actual environment. These short tests were used to analyze how well each system detected a person and a passenger vehicle (pickup), which are commonly involved in accidents. The tests involved temporarily mounting the proximity warning system on the rear of the truck near the top of the axle, then backing slowly toward a stationary person or a pickup. The detection zone was recorded for each test object and analyzed to determine if the zone was adequate to help avoid a collision. The frequency of false alarms was also observed by backing the truck up in a clear, flat area. For detailed information on test procedures, see SAE standard J1741 entitled "Discriminating Backup Alarm System Standard," and the NIOSH procedures in reference [2].

After the initial tests were completed, researchers chose the most promising systems for tests at a mine site. A cooperative agreement with Phelps Dodge Morenci, Inc., Morenci, AZ, was established that allowed NIOSH and system manufacturers to test systems on Caterpillar model 793 and 797 dump trucks used in mine production. On some trucks, evaluation forms were given to the truck drivers at the end of each shift, and they were asked to provide feedback on how the system was operating and if it was helpful. Researchers also collected performance data during direct observations, driver interviews, and by recording video footage of the blind area.

RESULTS

Preview Radar System

The Preview heavy-duty radar system[1] is manufactured by Preco Electronics, Boise, ID, and marketed for heavy equipment. The system uses pulsed radar to sense the presence of and determine the distance to an object in the radar beam. An alarm interface is mounted in the cab of the truck and has both audible and visual warnings. A series of LEDs light up in succession, and the warning tone changes frequency to indicate distance to an object.

NIOSH tested the first generation of the Preview radar system on a Caterpillar 793B (260-ton-capacity) dump truck at Phelps Dodge Morenci, Inc. The maximum range of the system for detecting a standing person was 8.5 m (28 ft), but a person could not be detected near the rear tires because of the narrow radar beam pattern (dashed line in figure 2). It is important that the entire width of the truck be covered near the tires. For this reason, NIOSH researchers requested that the radar system be modified to provide a wider beam. Instead, Preco introduced a new networked version of the system that allows two antennas to be used for each alarm interface. This dual-antenna system is also programmable to customize the detection zone shape and distance for a particular piece of equipment.

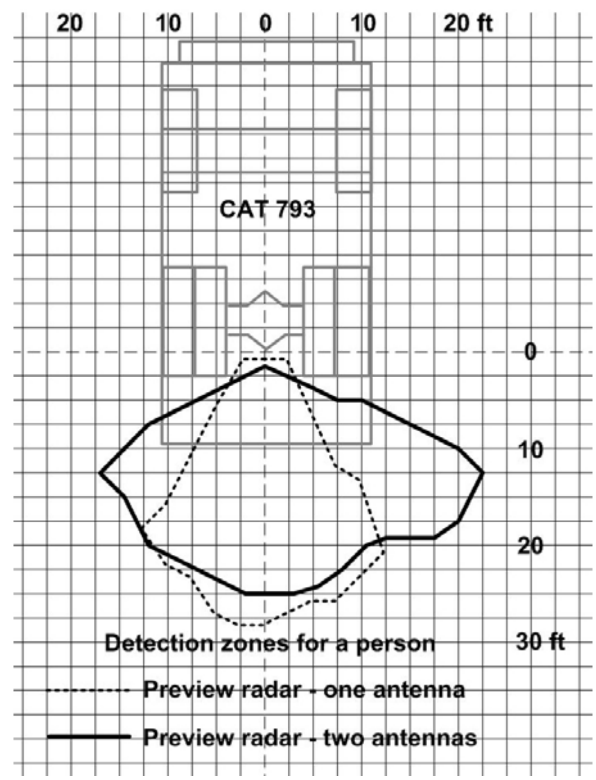

Figure 2. Comparison of detection zones for single- and dual-antenna Preview radar system.

Figure 3 shows the new radar system mounted on the back of a Caterpillar 793B. Two antennas were mounted approximately 1.8 m (6 ft) apart on special brackets attached to the rear axle area. Caterpillar

[1] Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

does not recommend welding objects directly onto the axle housing, so the brackets were attached using existing bolts. To achieve detection near the tires, the radar beams for each antenna were crossed slightly (an inward angle of approximately 20°). A single alarm interface, which accepts information from both antennas, was mounted in the cab. The solid line in figure 2 shows the resulting detection zone for a person and indicates that detection near the tires improved. The detection zone for a vehicle was similar.

Figure 3. Preview radar system with two antennas.

Several methods were employed to evaluate this system while the truck was in use. (1) Comment forms that provided information on false alarms, system effectiveness, and other general observations were available for drivers to fill out at the end of each shift; (2) informal discussions with drivers provided researchers with more-detailed information; and (3) a VCR recorded video from a camera on the rear of the truck along with radar system alarms so that objects seen in the video footage could be correlated with alarm information.

Tests of this radar system are in progress, but results so far have indicated the following:

• The radar system was effective in detecting people and smaller vehicles behind the truck;

• Occasional false alarms did occur, but not frequently enough to cause the system to be ignored. However, even infrequent false alarms made it evident that some method is needed to verify that no person or object was really in danger of being hit;

• Nuisance alarms (alarms from objects that the driver was already aware of) did occur. Again, some method of verifying the cause of the alarm is needed.

• After about 6 months of continuous use, one radar antenna failed due to vibration and had to be replaced.

Based on these findings, it is recommended that radar or other sensing systems be used in combination with camera systems. The camera should provide a view of the area that the radar is monitoring so that radar alarms can be verified without the driver leaving the cab. At the same time, radar compliments cameras by providing an important alarming function that prompts the driver to check the video monitor so that the possibility of a collision does not go unnoticed.

Electronic Tag-Based Systems

NIOSH has conducted short-term tests of systems that sense electronic tags worn by workers or mounted on other vehicles. These systems require a device on the truck that senses and communicates with the tags and an alarm interface in the cab. These systems operate in a very similar manner to radio-frequency identification (RFID) systems that are popular in security systems and asset tracking.

Two systems available for mining equipment have been tested so far: the Buddy System (Nautilus International, Burnaby, B.C., Canada) and the CAS/CAM system (Advanced Mining Technology [AMT], Chittaway Bay, NSW, Australia). Both systems were tested at NIOSH on a 50-ton-capacity off-highway dump truck. (The Nautilus system was also tested at Phelps Dodge Morenci on a 260-ton-capacity truck, but NIOSH researchers were not present, and test results are available only from Nautilus.)

The Buddy System uses a loop antenna mounted on the truck to transmit a low-frequency electromagnetic signal that surrounds the entire truck. Electronic tags worn on the belt of workers or mounted on smaller vehicles sense this signal's strength and send an alarm to the driver if the tag comes within a certain distance of the truck. An alarm can also be generated at the tag itself. Figure 4 shows the detection zone for a person wearing a tag. The area around an entire truck can be monitored with just one loop antenna, and the radius of the detection zone can be changed according to different equipment sizes and speeds. Multiple antennas can be used to monitor the front and back more equally and provide location information for a detected tag.

The CAS/CAM system uses a higher-frequency signal and requires one transceiver mounted on the front of the truck and one on the back for complete coverage. At the time of the tests, no tag was available for personnel (due to tag size), so a pickup truck was outfitted with a tag. The results of the detection tests are shown in figure 5. The tag was detected out to 17.4 m (57 ft), and the width of the detection area was adequate to sense the pickup immediately next to the rear tires or front bumper.

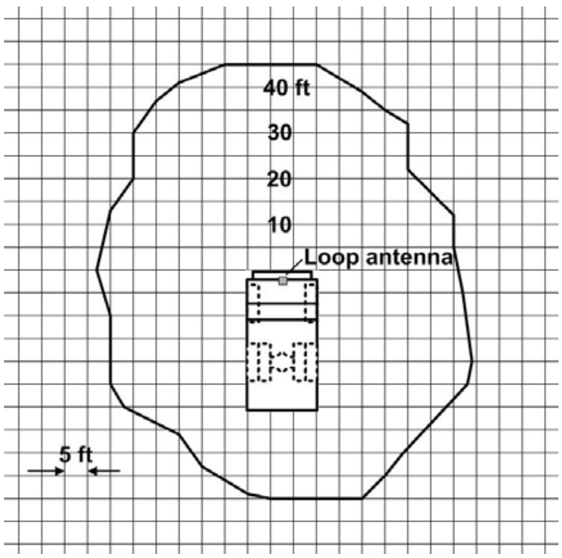

Figure 4. Detection zone for Nautilus Buddy system and person wearing tag.

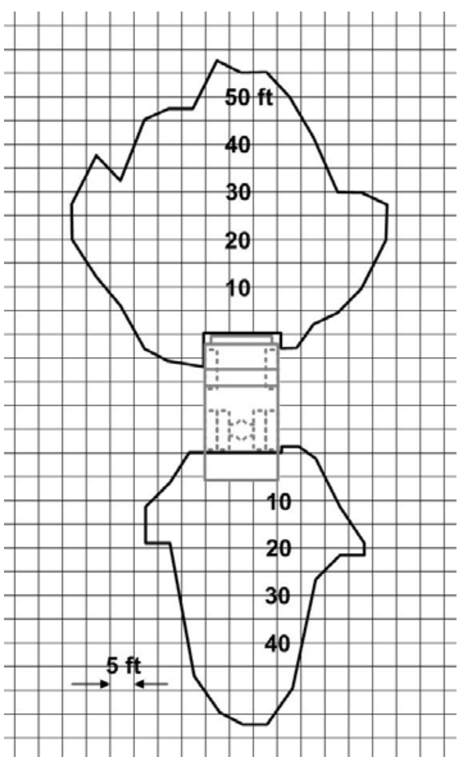

Figure 5. Detection zone for the CAS/CAM system with tag mounted on pickup truck.

One advantage of electronic tag-based systems is the very low occurrence of false alarms. Only objects or personnel outfitted with tags can be detected. A driver can be very certain an alarm is cause for caution. A disadvantage is that the cost of these systems is higher when compared to radar because of the number of tags required and the additional communications systems needed. The use of tags also raises maintenance issues, but the increased functionality of such systems may help offset the added cost. The alarm interface for these systems does not provide an exact location for the person or object causing the alarm, so cameras may again be helpful. In fact, the manufacturers of both systems recommend the use of cameras on the truck as part of their respective overall systems.

GPS-Based Proximity Warning System

Many surface mines have GPS systems on their equipment for tracking, dispatch, and positioning. NIOSH researchers proposed that these systems be taken one step further to provide the safety function of proximity warning. This idea was based on the fact that the location of much of the equipment in a mine site is already known via on-board GPS. All that is needed is to get this information to the drivers of the equipment. Cooperative research was initiated between NIOSH and Trimble to develop a system based on the available GPS technology used in mines. The system was to provide proximity warning information to drivers for stationary objects (e.g., dump points, buildings, utility poles) and moving objects (e.g., other dump trucks, smaller vehicles).

The concept for GPS-based proximity warning sensors for mining equipment entails the use of differential GPS receivers and radios on all equipment having reduced visibility, all smaller vehicles on a mine site, and eventually all workers on foot. The location of all moving equipment and personnel must be determined and updated in real time, and this information must be transmitted to all nearby equipment so that the operators are aware of other vehicles or workers nearby. In addition, the location of stationary structures needs to be stored in a database of potential obstacles. An alarm interface in the cab is required to provide a visual and audible warning when another vehicle, worker, or stationary obstacle is within a preset danger zone around the equipment.

Development of a GPS-based proximity warning system by NIOSH and Trimble began in 2000. Prototypes were tested in an outdoor laboratory setting on passenger vehicles. Development continued over the next 2 years, resulting in a mine-ready system that was demonstrated at the Phelps Dodge Morenci copper mining operation in April of 2002 [3].

The mine-ready system consisted of the following Trimble components mounted on each piece of mobile equipment: a GPS antenna; a Windows CE-based computer with LCD display to run the proximity warning software; an eight-channel, single-frequency, differential GPS receiver (integrated into the computer enclosure); and a SiteNet 900-MHz Internet Protocol (IP) radio for peer-to-peer communication between equipment (see figure 6). All these components were designed for use on heavy equipment. Each system uses GPS to determine the equipment's location. Differential correction information from a base station is used to correct the location. The corrected location is then transmitted once per second via the IP radio to all other mining equipment and smaller vehicles in the area. The locations of other vehicles are also received by the IP radio and shown on the computer's display if they are within a specified range. The location of stationary obstacles, such as dump points, power lines, and mine buildings, does not have to be transmitted; instead, their coordinates can be entered into the system's database so that they automatically show up on the vehicle's display screen.

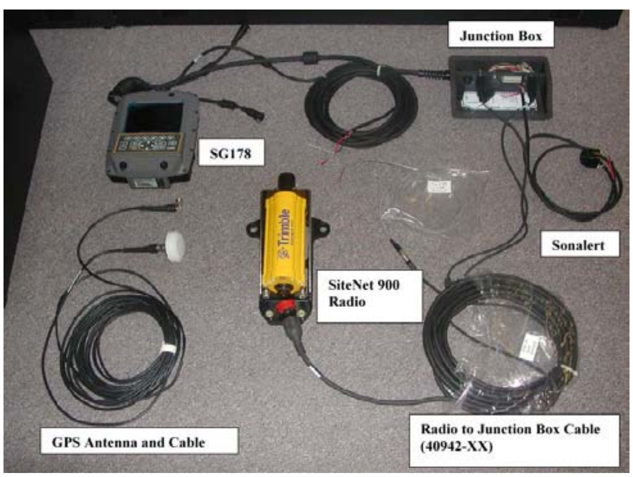

Figure 6. GPS system components.

Tests of the system were conducted at Phelps Dodge Morenci. System components were installed on a Caterpillar 797 360-ton-capacity haul truck, a Caterpillar rubber-tired dozer, and two service trucks (pickups). A base station was also installed on a nearby hill to provide differential correction information. The computer in the cab of each vehicle (figure 7) contained a screen for the equipment operator that displayed his/her equipment in the center, the detection zone radius, the warning zone radius, system status, and icons representing other vehicles or stationary obstacles in the area. Audible alarms were generated whenever another vehicle or stationary obstacle was detected in either zone. Also, the color of another vehicle's icon changed from green (outside both zones), to yellow (inside detection zone), to red (inside warning zone) as it approached the center of the screen.

Figure 7. Driver interface for GPS-based proximity warning system.

Each system successfully tracked three other mobile vehicles and six stationary obstacles. Expected accuracy of the position of a vehicle or obstacle shown on the system display was 2 to 5 m (6 to 16 ft) using the computer's internal receiver with differential correction. Accuracy depended on many factors, including satellite position (positional dilution of precision [PDOP]), multipath interference, the status of "selective availability" (SA), and the type of GPS receiver used, to name a few. Observed accuracy was 2 to 3 m (6 to 10 ft) during the tests. Greater position accuracies could be obtained using higher-quality GPS receivers.

For a mine-wide, GPS-based, proximity warning system to be effective, all vehicles, mining equipment, and workers on a mine property would need to be outfitted with a system. Functionality and cost of each system could vary with each type of vehicle. For instance, service trucks and contractor vehicles could be outfitted with a simple system that would not require the current computer and display set-up. Such a system could use an off-the-shelf GPS antenna and receiver, a low-cost processor, and an IP radio all packaged in a single enclosure that attached quickly to the vehicle's roof. A simple audible warning would be generated in the cab of the vehicle when another vehicle or piece of equipment was nearby.

The reduced visibility associated with larger mining equipment would require a more expensive and more functional system. A graphics display would be needed to allow the operator to locate and identify nearby obstacles. The system could stand alone like the mine-ready system described here, or it could be integrated into existing dispatch and control systems.

One obvious element missing from these tests is a system to protect a worker on foot. This would require a personal system that included miniature GPS equipment, a small processor, and IP radio equipment. The system would need to fit on the worker's belt or a vest pocket. With the exception of SiteNet radios, hardware for a personal system is available.

The preliminary tests at a surface mine showed that a GPS-based proximity warning system has the potential to significantly reduce accidents involving collisions or driving over an edge at surface mining operations. Future work will involve larger-scale and longer-term tests to prove this technology adequately. Also, several improvements need to be made to the proximity warning algorithms, such as the integration of dead-reckoning methods and the ability to use pseudolite (ground-based GPS transmitter) signals when needed. The ability to protect workers on the ground will be the final element needed to complete this system.

Computer-Assisted Stereo Vision

As tests of the radar system showed, it would be beneficial to combine sensor technologies with cameras so that an alarm could prompt a driver to check the camera view. A new technology under development could integrate cameras and alarming into one system by using a computer to process video data from stereo cameras. Researchers at the Colorado School of Mines (CSM), Golden, CO, have developed a stereo imaging system as part of an automated ore loading system. Application of this system to the proximity warning problem in surface mines is being studied through a cooperative effort with NIOSH [4].

Figure 8 shows the principle behind calculating the distance to an object using stereo imaging. If an object is viewed by both cameras and camera parameters are known, then the distance to the object can be calculated from the disparity between the projected position of the object on the image planes. Note the difference between u_1 and u_2 in the figure. The distance to an object is calculated as—

$$z = \frac{fd}{(u_2 - u_1)}$$

where z = distance to the object,
f = distance from lens to imaging plane,
d = distance between lenses,
u_1 = projected position of object on image plane 1,
and u_2 = projected position of object on image plane 2.

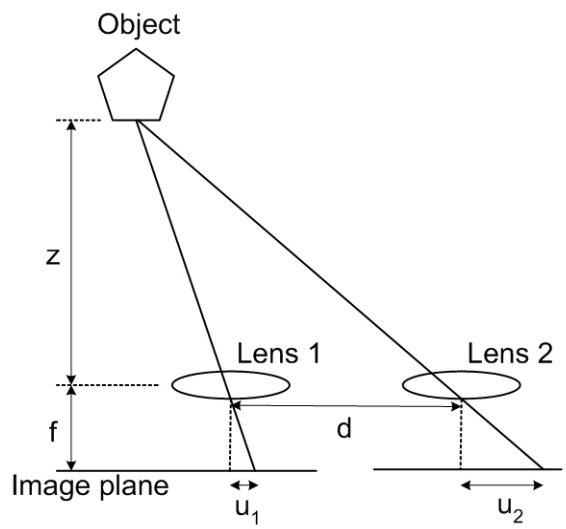

Figure 8. Geometry of stereo imaging and distance calculation.

The prototype system being developed consists of a stereo camera head attached to a laptop computer via a Firewire (IEEE 1394) interface. A pair of images is captured from each camera and stored on the computer. To find a feature within the images that is common to an image pair, intensity-based correlation is used. This requires pixel regions to be compared in both images along epipolar lines. When an intensity match is found for a particular region, then the disparity between the two regions can be calculated and converted to a distance. A statistical approach is used to calculate the distance to the ground plane. An object that stands above the ground plane by some preset distance would cause an alarm. For a more detailed description of the algorithm, see [6].

Figure 9 shows an image captured during a test at a quarry. The stereo cameras were mounted on the rear of an off-highway dump truck. The light-colored (green) boxes represent areas identified on the ground.

The darker (red) boxes represent items that stood out from the ground and would cause an alarm. The pickup truck, people, and car in the background were correctly identified as objects that would cause an alarm. Other tests were conducted to see if the system would correctly detect a person or berm in the path of the truck. The results of these tests were promising.

With the system described here, calculations on image pairs were done after video footage had been collected. Future work will involve modifications to the software for image capture, distance calculation, and alarming, with updates to be run one or two times per second. Other issues still need to be studied, such as the effects of camera vibration, lighting conditions, and hardware limitations.

Figure 9. Captured image from one stereo camera with ground and alarm areas identified.

SUMMARY

Devices are available to help eliminate blind spots and associated accidents involving off-highway mining equipment. Camera systems and, more recently, radar and electronic tag-based systems designed specifically for heavy equipment are on the market. Successful implementation of these systems can be achieved if their advantages and shortcomings are realized and anticipated. Radar is effective in detecting people and small vehicles, but it is susceptible to false and nuisance alarms, thereby requiring a supplemental method, such as cameras, to verify the cause and exact location of the nearby object. Tag-based systems, while more expensive than radar, have the advantage of producing very few false alarms and may be configured for tag-in/tag-out functionality. Cameras can benefit from the addition of either of these sensor systems so that an equipment operator is prompted to check the video monitor before and during equipment movement.

Novel approaches have also been taken to solve this problem, such as the use of GPS and a wireless network to transmit a vehicle's location to all other vehicles in the area. This system is in the development stage, but shows promise for mines that already have a GPS infrastructure in place. Finally, a new system under development at the Colorado School of Mines uses computerized image processing and stereo cameras to detect the presence of workers, vehicles, or other obstacles. At the same time, the system provides a camera view of the equipment's blind area to the operator.

An ideal proximity warning system would provide detection of obstacles and workers anywhere near the mining equipment and provide the operator with information on the exact location, number of detections, and type of obstacle detected. False alarms with this system would be rare, and small rocks, ruts, or foliage in the roadway would not cause an alarm. The system's detection zone would adjust in size and shape according to vehicle's size and speed. And finally, the system would be robust enough to handle the vibration and shocks typical of mining equipment and the extreme environmental conditions found on mine sites. NIOSH researchers will continue to work toward these goals and promote the use of effective technologies in order to decrease collisions involving mining equipment.

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