Recent advances in proximity warning technology for surface mining equipment

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Abstract

The lack of visibility near earthmoving equipment results in an average of five fatalities in U.S. surface mines each year. These accidents occur when equipment strikes another vehicle, strikes a worker or travels over the edge of an embankment. Researchers at the U.S. National Institute for Occupational Safety and Health evaluated off-the-shelf proximity warning systems that sense obstacles near the equipment and provide an alarm to the operator. Limitations of existing systems have necessitated the development of new systems designed specifically for mining equipment, including a global positioning system-based proximity warning system and a computer-assisted stereovision system. A description of these two new systems and preliminary test results are discussed.

Introduction

The lack of visibility near large earthmoving equipment resulted in six fatalities in U.S. surface mining operations in 2002. These accidents were caused by equipment striking another vehicle, striking a worker or traveling over the edge of a road or dump point. The yearly average for these types of accidents during a recent five-year period was approximately five fatalities (MSHA, 1997-2000). There is clearly a need to provide better information to equipment operators regarding their surroundings.

Researchers at the U.S. National Institute for Occupational Safety and Health (NIOSH), Spokane Research Laboratory, are working to reduce these accidents by testing and developing systems that sense obstacles and sudden changes in terrain near the equipment and provide this information to the operator. Limitations of off-the-shelf proximity warning systems designed for other industries have necessitated the development of new systems designed specifically for surface-mining equipment. These limitations included false alarms, limited detection range, a lack of specific information on an obstacle (location and identity), inability to detect sudden changes in terrain (dump points in particular) and problems withstanding the environment (Ruff, 2000).

To address these problems, NIOSH is cooperating with other organizations to develop a proximity warning system based on the global positioning system (GPS) and a computer-assisted stereovision system. A prototype of a GPS-based system was developed in cooperation with Trimble, Sunnyvale, CA, and prototypes were tested at Phelps Dodge Morenci, Morenci, AZ (Ruff and Holden, 2002). A proximity warning system based on stereovision technology is being developed in cooperation with the Colorado School of Mines, Golden, CO (Steele et al., 2003).

GPS-based proximity warning system

Many surface mines have GPS systems on their equipment for tracking, dispatching 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 by 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 equipment operators for stationary (dump points, buildings and utility poles) and moving (other dump trucks and smaller vehicles) objects.

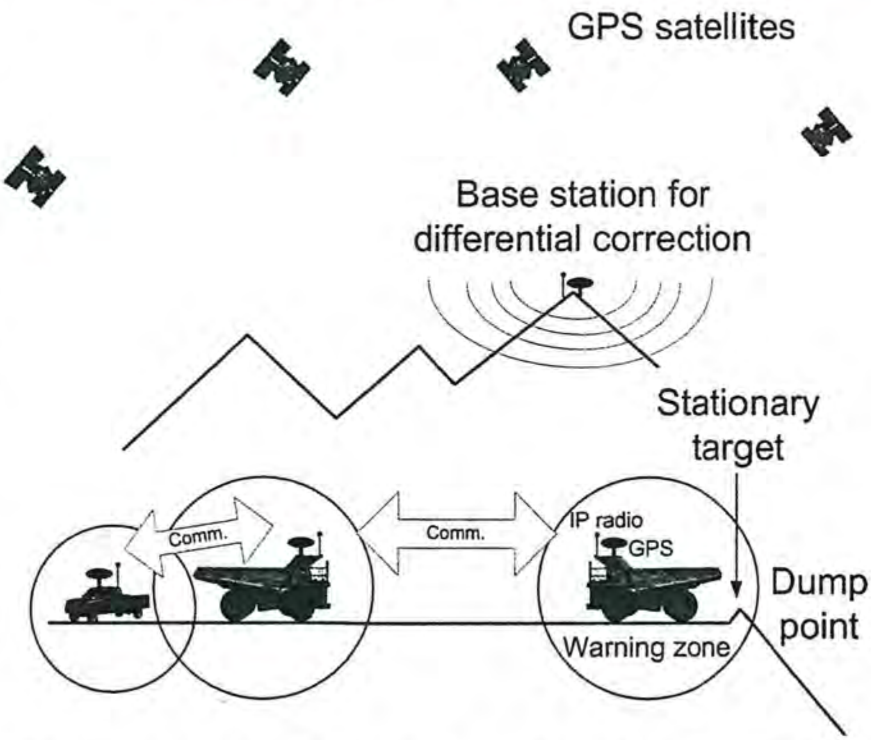
Application. The concept for GPS-based proximity warning for mining equipment entails the use of differential GPS receivers and radios on all equipment having reduced visibility, all smaller vehicles on a mine site and eventually all workers on foot (Fig. 1). The location of all moving equipment and personnel must be determined and updated in real time, and this information must be transmitted to all equipment in the area so the operators are aware of other vehicles or workers nearby. In addition, the locations of stationary structures need 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.

In 2000, NIOSH and Trimble began development of a GPS-based proximity warning system. Prototypes were tested in an outdoor laboratory setting on passenger vehicles. Development progressed during a two-year period. It resulted in a mine-ready system that was demonstrated at the Phelps Dodge Morenci copper mining operation in April 2002.

The mine-ready system consisted of the following Trimble components mounted on each piece of mobile equipment: a GPS antenna; a Windows[1] 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.

FIGURE 1

The concept of a GPS-based proximity warning system.



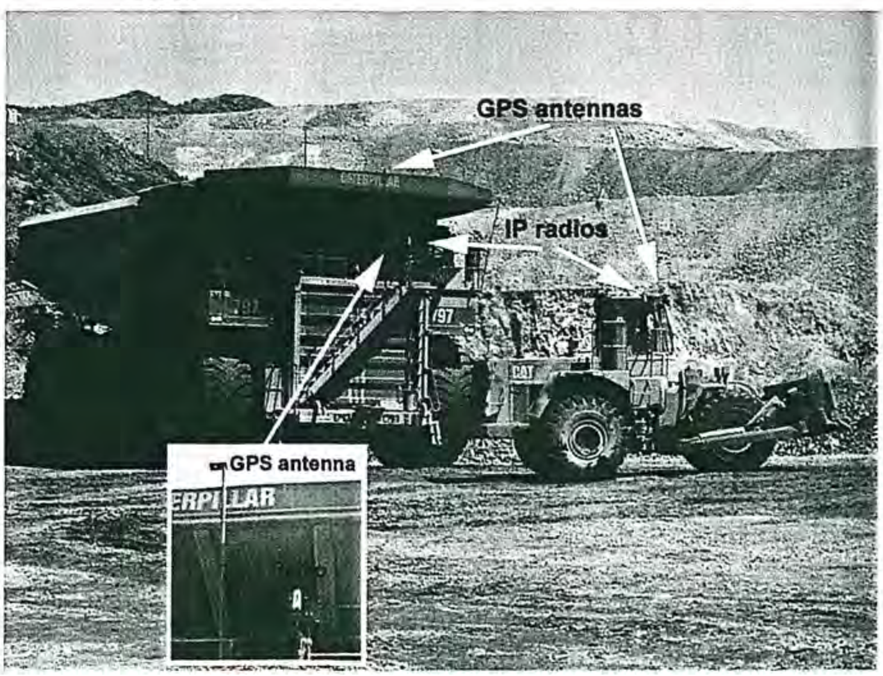
All these components were designed for use on heavy equipment. Each system uses GPS to determine the equipment's location. Differential correction information from a base station is used to correct the location. The corrected location is then transmitted once per second by the IP radio to all other mining 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 locations of stationary obstacles, such as dump points, power lines and mine buildings, do 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.

Tests of the system were conducted at Phelps Dodge Morenci. System components were installed on a Caterpillar 797 397-t (360-st) haul truck, a Caterpillar rubber-tired dozer (Fig. 2) and two service trucks. A base station was also installed on a nearby hill to provide differential correction information. The computer in the cab of each vehicle (Fig. 3) 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.

Results. Each system successfully tracked three other mobile vehicles and detected six stationary obstacles.

FIGURE 2

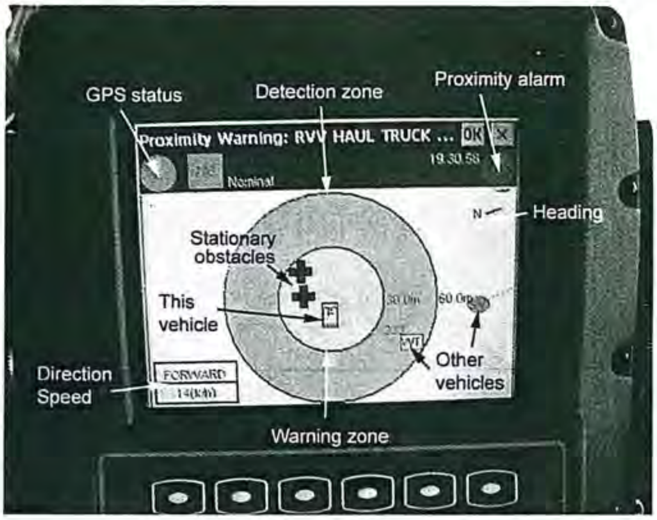
Tests of a GPS proximity system on a Caterpillar 797 haul truck and dozer.



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

FIGURE 3

Driver interface for GPS-based proximity warning system.



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 or PDOP), multipath interference 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.

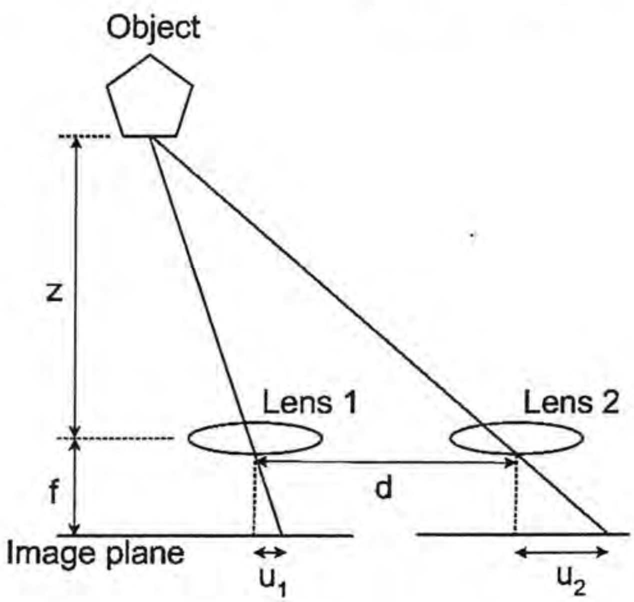
The reduced visibility associated with larger mining equipment would require a system with functionality similar to the current prototypes. A graphics display would be needed to allow the operator to locate and identify nearby obstacles. The system could stand alone like the mine-ready system described here. It could also be integrated into existing dispatch and control systems.

One element missing from these tests is a system to protect a worker on foot. This would require an inexpensive 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 in a vest pocket. With the exception of SiteNet radios, hardware for a personal system is available and software development is planned to begin in the near future. Cost of the components would need to be reduced before implementation would be feasible.

The preliminary tests at a surface mine showed that a GPS-based proximity warning system has the potential to 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 will 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 the view to satellites is obstructed. The ability to protect workers on the ground will be the final element needed to complete this system.

FIGURE 4

Geometric relationship of stereo image pair.



Computer-assisted stereo vision

While cameras have been mounted on the back of haul trucks before, their effectiveness requires the active attention of the driver if obstacles and terrain changes are to be observed — attention that is better focused on the road ahead. Recent developments in machine vision, both hardware and software, have made it possible to develop economical stereo-imaging systems that can actively assist drivers in monitoring blind areas near the equipment. Research at the Colorado School of Mines began with the application of stereo imaging to assist an autonomous loader in identifying a pile of rock. During development of this system, it was hypothesized that the system could be used for safety by identifying when personnel were in the path of the equipment and in danger of being hit. With cooperation from NIOSH, the concept was tried on surface mining equipment.

With stereo imaging, the distance to objects and their size can be computed by the system. An algorithm can then be run that establishes whether any objects or terrain changes (berms and edges) are in the vicinity of the haul truck. If obstacles are detected, the driver can then be notified and the appropriate action can be taken.

Application. Figure 4 shows the principle behind calculating the distance to an object using stereo imaging. If a common feature is viewed by both cameras and the camera parameters are known, then the distance to the

FIGURE 5

Correlation-based feature detection used on an underground muck pile.

feature can be calculated from the disparity between the projected position of the feature on the image planes. Note the difference between $u1$ and $u2$ in the figure.

The distance to a feature is calculated by

$$z = \frac{fd}{\left(u_2 - u_1\right)} \tag{1}$$

where
z is the distance to the feature,
f is the distance from lens to imaging plane,
d is the distance between lenses,
$u1$ is the projected position of feature on image Plane 1 and
$u2$ is the projected position of feature on image Plane 2.

This methodology depends on successfully identifying common features in each image pair. Features are identified and correlated based on their unique grayscale values and assumptions on the limitations of where a feature can occur within each image. First, the two images are transformed so the two backplanes are parallel (if they are not already), and the elevations in the two images are aligned. Then the images are "normalized," meaning the light intensity over the whole image is averaged and the two images are adjusted to the same level. Once these operations have been completed, the feature detection algorithm is run on both images by comparing grayscale values for each pixel using an average of its nearest neighbors in a 15- x 15-pixel square. Features are identified as locations that have a unique grayscale match between the two images, as illustrated in Fig. 5. The range to each feature is then calculated as described earlier.

The process of identifying features and establishing three-dimensional position in a scene can be applied to haul-truck safety. If there are no obstacles near the rear of the truck, then the features detected will all lie in or near a plane that is the best fit to the ground plane behind the vehicle. Outliers or features that do not fit within an acceptable distance above or below this plane could be indicators of the presence of obstacles.

Results. The images that follow were taken at the Aggregate Industries Quarry in Morrison, CO. The feature detection algorithm was run on these images, and

FIGURE 6

People and pickups behind a haul truck.

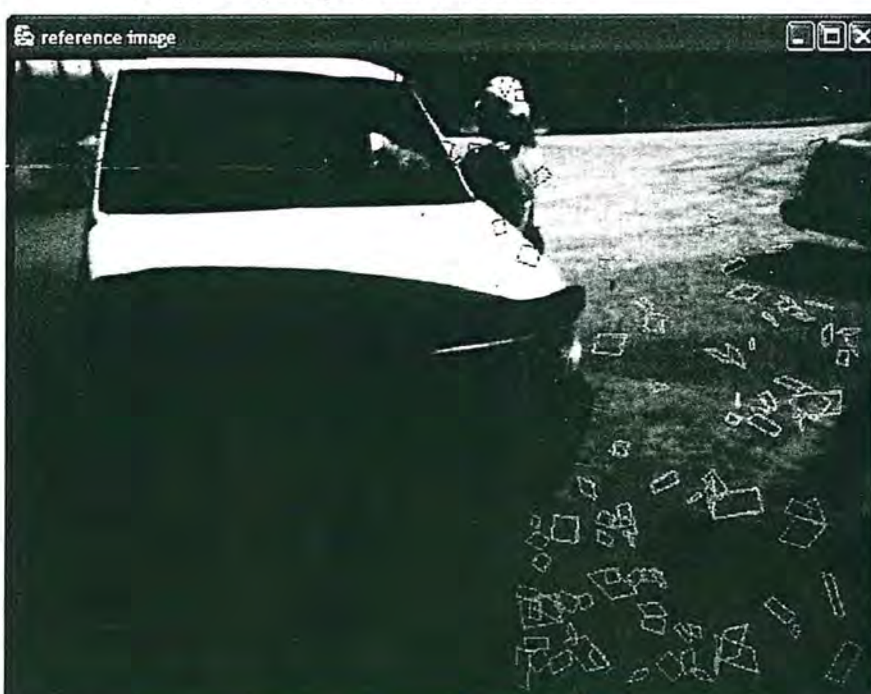


FIGURE 7

Berm detection.

features were collected into groups called patches if they contained similar three-dimensional geometric information — they were in nearby locations and had similar planar characteristics. In these images, green patches represent areas that were identified as related and near the established ground plane. Red rectangles represent contiguous areas or patches that were not within the acceptable deviation from the ground plane and are thus identified as obstacles.

Figure 6 shows a view from the back of a parked haul truck where a number of obstacles have been detected. All the red patches are collections of features that are recognized as being out of the ground plane. Note that the system only collects a set number of features so these represent the "best" three-dimensional information as computed by the correlation-based stereo detection algorithm. The authors are encouraged by the results of Fig. 6, where the algorithm detected a truck, a person, and even the leg of one of the authors, but ignored the shadow cast by that leg. Figure 7 is an image of a berm at the quarry as seen from the back of the vehicle. While it is somewhat difficult to discern the transition from the ground plane to the berm by eye, the imaging system accurately detected it.

While these results show promise, the key to safety will be error-free alarming to the operator. This will require robust algorithms for determination of real obstacles rather than noise and/or virtual obstacles. If the operator is to trust the system, it must provide reliable information. So false positives must be minimized and no real alarms can be missed. To produce a field-ready system, more testing under different conditions will be required including vehicle motion and varying lighting.

Summary

New proximity warning systems are being developed by NIOSH, in cooperation with other researchers, to address the challenges of sensing workers, small vehicles and changes in terrain near large surface mining equipment. Novel approaches have been taken, such as the use of GPS and radios to track vehicles and warn of sudden changes in nearby terrain. This system is in the development stage, but shows promise for mines that already have a GPS infrastructure in place. Also, a new system under development at the Colorado School of Mines uses computerized image processing and stereo cameras to detect the presence of obstacles. An alarm is provided to the driver if an obstacle is detected and, at the same time, the system provides a camera view of the equipment's blind area.

Researchers are working toward the ideal proximity warning system that 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. The system's detection zone would adjust in size and shape according to the vehicle's size and speed. 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.

No proximity warning system can completely replace the training and caution necessary for operating heavy equipment. However, technology can help reduce some of the guesswork required when operating equipment having extensive blind spots. ■

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