# Preprint 04-03

## 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 a piece of equipment either strikes another vehicle or worker, or travels over the edge of an embankment. Researchers at the National Institute for Occupational Safety and Health have 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 GPS-based proximity warning system and a computer-assisted stereovision system.

### INTRODUCTION

The lack of visibility near large earthmoving equipment resulted in six fatalities in U.S. surface mining operations during 2002. These accidents were caused either by a piece of equipment striking another vehicle or worker, or the equipment traveling over the edge of a road or dump point. The yearly average for these types of accidents during the previous 5 years was approximately five fatalities (Mine Safety and Health Administration [MSHA], 1997-2000). There is clearly a need to provide better information to equipment operators regarding their surroundings.

Researchers at the National Institute for Occupational Safety and Health (NIOSH), Spokane Research Laboratory, are working to reduce these accidents by testing and developing systems that (1) sense obstacles and sudden changes in terrain near the equipment and (2) provide this information to the operator. Many off-the-shelf proximity warning systems that were developed for automobiles, light trucks, and construction equipment were evaluated on off-highway dump trucks (Ruff, 2000). These systems typically consist of a sensor mounted on the vehicle that detects the presence of an obstacle and an alarm (audio and/or visual) mounted in the cab that pro-vides a warning to the driver. Limitations were found with existing systems, including false and nuisance alarms, limited detection range, a lack of specific information on an obstacle (e.g., location, identity), inability to detect sudden changes in terrain (dump points in particular), and problems withstanding the environment. These limitations have necessitated the development of new systems that address both the detection of obstacles and dump points and are designed specifically for large, off-highway haulage equipment.

NIOSH is cooperating with other organizations to develop innovative technologies that address the above concerns. Researchers are working with manufacturers of existing systems to modify them for large mining equipment. Other cooperative work is being conducted to develop new systems such as 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, 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 equipment operators for stationary (e.g., dump points, buildings, utility poles) and moving (e.g., other dump trucks, smaller vehicles) objects.

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 (figure 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 that the oper-ators 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 inter-face 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.

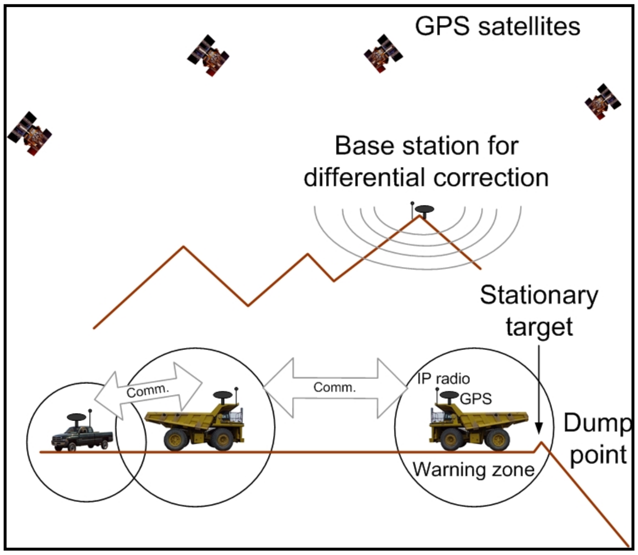


**Figure 1. The concept of a GPS-based proximity warning system.**

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 has progressed over the last 2 years, resulting in a mine-ready system that was demon-strated at the Phelps Dodge Morenci copper mining operation in April of 2002.

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 (figure 2). 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 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, Inc. System components were installed on a Caterpillar 797 360-ton-capacity haul truck, a Caterpillar rubber-tired dozer (figure 3), 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 (figure 4) 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 2. GPS system components. Left to right: GPS antenna, computer and display with integrated receiver, and IP radio.**

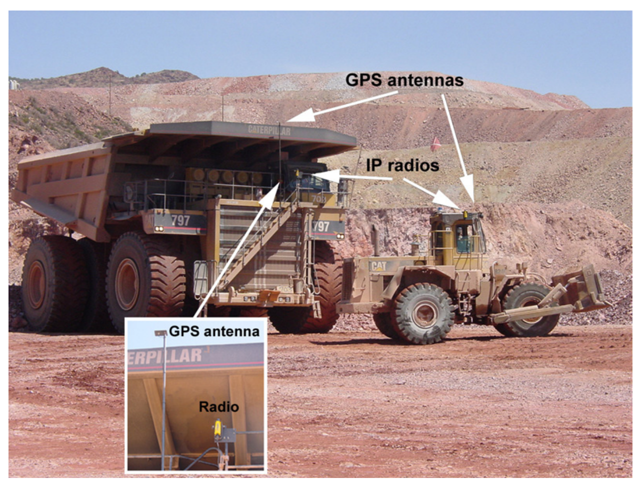


**Figure 3. Tests of GPS system on a Caterpillar 797 and dozer.**

Each system successfully tracked three other mobile vehicles and detected 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

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

position (positional dilution of precision [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.


**Figure 4. Driver interface for GPS-based proximity warning system.**

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 used. 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, 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, and software development is planned to begin in the near future.

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 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.

## COMPUTER-ASSISTED STEREO VISION[2]

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 be used in the field. 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, edges, etc.) are in the vicinity of the haul truck. If obstacles are detected, the operator can then be notified, and the appropriate action can be taken. This reduces the burden on the operator, provides relevant information when it's needed, and enhances the safety of the operation.

### Application

Figure 5 shows the principle behind calculating the distance to an object using stereo imaging. If a common feature is viewed by both cameras and camera parameters are known, then the distance to the feature can be calculated from the disparity between the projected position of the feature on the image planes. Note the difference between $u_1$ and $u_2$ in the figure.

The distance to a feature is calculated as

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

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

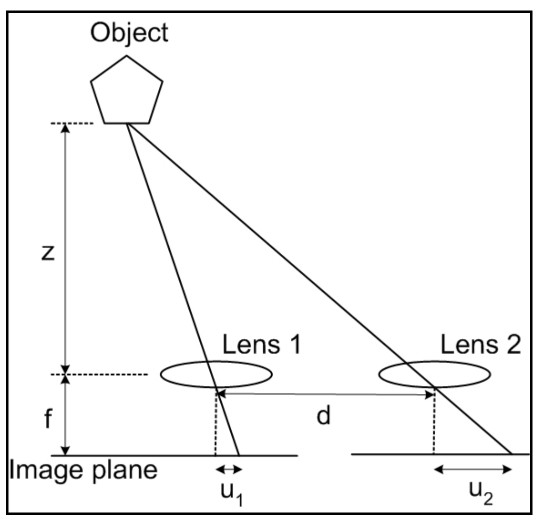


**Figure 5. Geometric relationship of stereo image pair.**

[2] The work in this section was supported by Cooperative Agreement U60/CCU816929-02 from the Department of Health and Human Services, Center for Disease Control and Prevention (CDC). Its contents are solely the responsibility of the author and do not necessarily represent the official views of the Depart-ment of Health and Human Services or CDC.

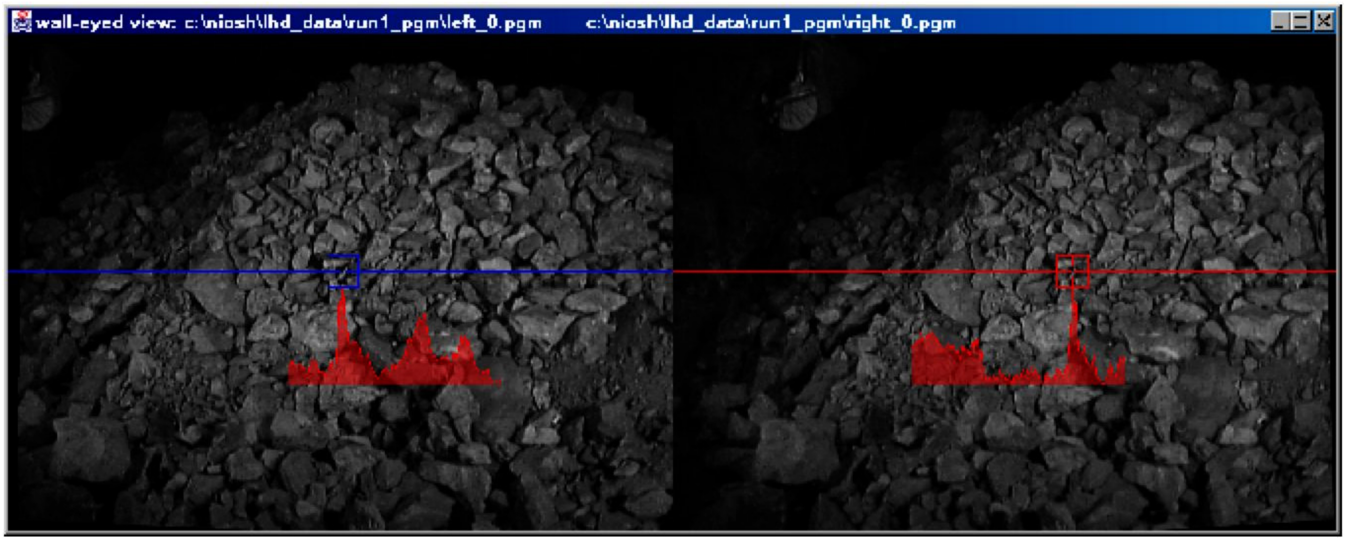


**Figure 6. Correlation-based feature detection used on an underground muck pile.**

Common features in an image pair are identified and correlated based on their unique gray-scale values and assumptions on the limitations of where a feature can occur within each image. Specifically, a feature must be located along the same epipolar line within the image, i.e., along the equivalent light plane that intersects the two camera backplanes. The intersection of a specific light plane with the camera backplane (imaging surface) results in a line, called the epipolar line. To enhance the speed of image processing and correlation, the two images are first rectified. This means 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. In addition, 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 using a 15- by 15-pixel square, i.e., the value at any pixel location is the average of its 15-by-15 nearest neighbors. The algorithm then seeks locations in each image where the same average gray-scale value is located. Features are identified as locations that have a unique match between the two images. An example is shown in figure 6.

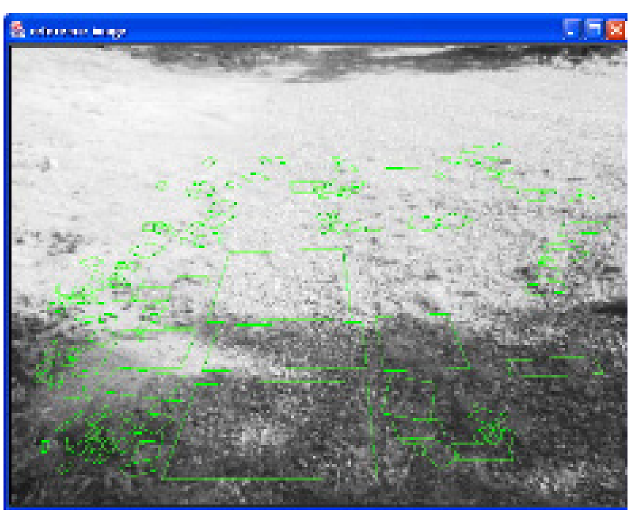

**Figure 7. Driveway showing assembly of patches**


**Figure 8. People and pickups behind haulage truck**

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 (trucks, people, abrupt changes in slope) 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. In these images, the ground plane was established by using the elevation angle of the stereo head (a single unit that contains both cameras) and the known distance to the ground to define a plane. The feature detection algorithm was run on these images, and features were collected into groups called patches if they contained similar three-dimensional geometric information, i.e., they were in nearby locations and had similar planar characteristics. In these images, green (light gray) patches represent areas that were identified as related and are near the established ground plane. Red (dark gray) rectangles represent contiguous areas or patches that are not within the acceptable deviation from the ground plane and are thus identified as obstacles. Figure 7 shows an empty landscape where all of the patches are identified as being "on the ground."

Figure 8 shows a view from the back of a parked haul truck where a number of obstacles have been detected. All the red (dark gray) 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. We are encouraged by the results of Figure 8, where the algorithm detected the leg of one of the authors, but ignored the shadow cast by that leg.

Figure 9 is an image of the boundary 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.

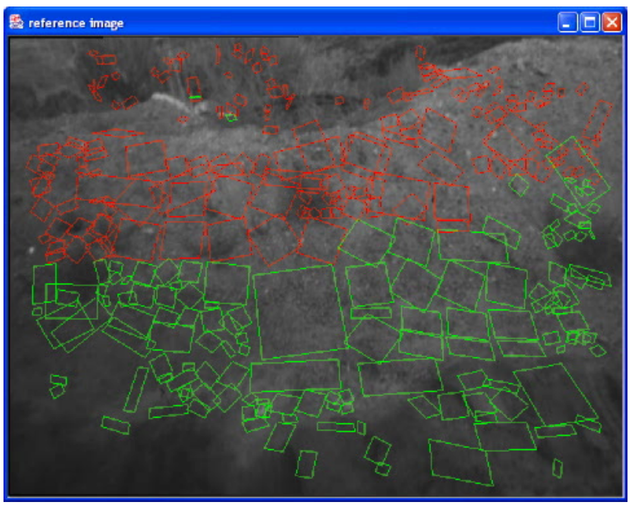


**Figure 9. Berm detection.**

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 and use the system, it must provide reliable information. Thus false positives must be minimized, while at the same time we must make sure that no real alarms are missed. To produce a field-ready system, more testing under a variety of conditions will be required.

## SUMMARY

Devices are available to help eliminate blind spots and associated accidents involving heavy equipment. Camera systems and, more recently, radar and electronic tag-based systems designed specifically for off-highway equipment are on the market. NIOSH researchers have tested many of these systems and found that, while they do have limitations for surface mining applications, they can alert a driver when an obstacle is near the equipment. Researchers are working to improve on these methods by developing new systems that can address the specific problems encountered in surface mining, i.e., collisions with vehicles and people, driving over the edge of dump points or roads, and the harsh environment.

Novel approaches have been taken to address these problems, 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, workers, and terrain changes 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 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. While no proximity warning system can completely replace the training and caution necessary for operating heavy equipment, technology can aid in reducing some of the guesswork required when operating equipment having extensive blind spots.

## ACKNOWLEDGMENTS

The authors would like to thank Thomas Holden and his project team at Trimble for their work in the development of the GPS-based proximity warning system and Jim Hanson of Phelps Dodge Morenci and Nathan Lowe of NIOSH for their contributions in the planning and implementation of tests for the GPS-based system. We would also like to gratefully acknowledge the cooperation and assistance provided by Aggregate Industries and their employees Pat Stuart and Damian Murphy for support of the field work at their quarry.

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