Mine Eyes

Proximity Alert for Monster Trucks

July 1, 2002

By: Todd M. Ruff, Thomas P. Holden
GPS World

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Imagine driving a three-story house while using only a few small windows, and you will have an idea of what it is like driving many of the dump trucks currently used in surface mining. A system combining GPS receivers, rugged computers, and wireless communications tells equipment operators the location of nearby equipment and obstacles, and warns them when they get too close.

Think of the biggest vehicle you have ever driven - perhaps a large rented moving van. Make that vehicle 25 times bigger and increase its load capacity by a factor or 100 - but cut driver visibility to a small fraction. Now picture yourself maneuvering this behemoth inside an open pit mine, around fixed obstacles, other moving vehicles, and workers on foot.

That is the daily challenge for the operators of the giant dump trucks used in surface mines. As a result, each year, an average of 20 accidents and three fatalities occur involving collisions between a piece of surface mining haulage equipment and either a smaller vehicle, a worker, or some other object. Another 21 accidents occur and three mining equipment operators are killed each year when their equipment backs over the edge of an embankment, stockpile, or dump point.

To help prevent these accidents, researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH), in cooperation with a large GPS manufacturer, are developing a proximity

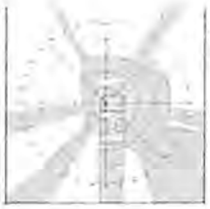

Figure 1: Gray areas indicate where the driver cannot see..Click to Enlarge

warning and edge detection system based on differential GPS technology and wireless network communications. This system provides equipment operators with the locations of nearby equipment, small vehicles, workers on foot, and stationary obstacles. To be effective, this system requires an accuracy of two meters or better.

We tested the first prototypes in a parking lot on passenger cars. Since then, we have developed a mine-ready system, consisting of a GPS receiver and antenna, a small computer with LCD display, proximity warning software, and a 900-MHz Internet protocol (IP) radio. We tested the system at the Phelps Dodge Mine in Morenci, Arizona, on two pieces of haulage equipment and two service vehicles.

Blind Areas

The trend toward bigger haulage equipment of all types has raised in safety issues involving operator visibility. The blind areas around a piece of mining equipment can be extensive. Figure 1 shows the blind areas around a 50-ton-capacity dump truck common in construction and sand and gravel operations. The gray shaded area shows those areas where the truck operator cannot see the ground. Mining operations use much larger trucks, up to 360-ton capacity, and the blind areas can extend 12 meters in front of the truck. The rear and right side blind areas can be even larger. Recent accidents attributed to blind areas include a dump truck that backed over the edge of a dump point, a dump truck that drove over a small pickup truck, and a front-end loader that crushed a worker on the ground.

Challenges. Several technologies have been applied to the problem of monitoring blind areas around large equipment. To date, however, mines have used only video cameras extensively. Systems based on radar or on the detection of electromagnetic fields around the equipment are in the development and testing stages and have not seen widespread use. The harsh mining environment and the size of the equipment in use present significant challenges for existing technology.

GPS in the Mines. Today, many surface mines use GPS-based location technology in their day-to-day operations - for surveying, ore body delineation, dispatching and tracking trucks, precise positioning of drill equipment, and real-time assistance to dozer operators for grade control. A logical next step is to use GPS technology to track equipment, vehicles, workers on foot, and stationary structures and warn operators when they are dangerously close to one of these things. The advantages of using GPS technology for proximity warning in mining applications include

- the ability to use the existing GPS infrastructure at many mines,
- the system's accurate location and tracking abilities,
- low to zero occurrence of false alarms,
- the capability of the system to identify obstacles, and
- customizable interfaces and warning zones.

System Development and Testing

The concept for GPS-based proximity warning for mining equipment, as illustrated in Figure 2, entails the use of differential GPS receivers and radios on all equipment with reduced visibility, all smaller vehicles on a mine site, and all workers on foot. The location of all moving objects must be determined and updated in real time, and this information must be transmitted to all nearby equipment so that equipment operators are aware of other vehicles or workers nearby. In addition, the location of stationary structures, such as buildings, utility poles, and dump points, are 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 (PWS) began in 2000 and we tested prototypes in an outdoor laboratory setting. The first system consisted of off-the-shelf GPS and wireless network components and laptop computers. Preliminary tests involving two passenger vehicles showed that the concept was feasible. Development has progressed over the last two years resulting in a mine-ready system that was demonstrated at the Phelps Dodge Morenci Mine in April of 2002.

Figure 2: The concept of a GPS-based (PWS)..Click to Enlarge

Prototype System. We built the prototype to demonstrate the feasibility of a GPS-based PWS. To keep costs at a minimum, we used readily available components. Each system consisted of a laptop computer to

- collect, process, and transmit data,
- run the PWS software, and
- provide a display for the vehicle operator.

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We used an off-the-shelf, 12-channel, differential GPS receiver and GPS antenna to determine location, a Coast Guard beacon to provide differential corrections, and a PCMCIA wireless network card (IEEE 802.11b) to communicate between laptops. We mounted each system in a passenger car for dynamic tests.

Prototype Tests. The prototype system went through a series of operational and performance tests using two vehicles - a local one and a rover. Our goal was to compare the actual operation of the various pieces with the system's specifications. These included the ability to set up, control, and monitor the GPS receiver properly and the ability to send and receive information over the wireless local area network (LAN) connection.

One key factor was to determine the reliable transmission range of the wireless LAN. We tested maximum (11 Mbps) and minimum (1 Mbps) signaling rates using the PWS software running on two laptops with wireless LAN cards installed. Each LAN card had a dual-patch diversity antenna directly mounted on it.

The system functioned very well when separated by distances under 60 meters and had no data loss. Beyond 60 meters, performance declined. Maximum transmission ranges were 120 meters for the 11-Mbps signal and 220 meters for the

1-Mbps signal. It was evident that the quality of signal reception is a function of range, antenna properties, and line-of-sight to the transceiver. With better antenna design and placement, signal reception can be made more reliable at longer ranges.

Another important test of the wireless communications was the time-to-associate measure for a new vehicle entering a local area. At ranges of up to 60 meters, the new vehicle associated, or was recognized, in less than one second. Outside 60 meters, the vehicle's time-to-associate was related to signal quality.

Performance Tests. A second set of tests evaluated the performance of the system. For this phase, we examined five cases: static to static, static to kinematic, kinematic to static, kinematic to kinematic, and vertical difference. All tests used a PWS in both a stationary local vehicle and a rover vehicle. We recorded data for both the local and rover vehicles throughout the tests, which covered the following items:

- The ability of the PWS to transfer information accurately, which was measured by matching received data from a rover vehicle and data from the local vehicle using GPS time tags.
- The latency of the rover vehicle information.
- The accuracy of the real-time vehicle position.
- The response to various dynamics of the rover vehicle.
- The response to various dynamics of the local vehicle.

Tracking the Rover. Provided the communications link between the vehicles was functioning, the local vehicle's PWS could follow the trajectory of the rover vehicle according to the transmitted information. We determined errors by matching real-time data stored by the rover system with the perceived rover data recorded by the local PWS using a GPS time mark corresponding to the transmitted information. Essentially, we matched the information in time so as to remove all latency errors. The results showed that the errors introduced to the system by corrupt data transmissions were negligible.

The latency of the information presented to an operator corresponds to errors in the actual position of the rover vehicle. Latency-induced error is dependent upon the velocity of the rover vehicle. Latency can be determined by special methods to roughly 0.2 seconds assuming a broadcast rate of 4 Hz. In the tests, observed latency correlated well with this value. Additional sources of latency could be attributed to radio and processing delay. Overall, we measured the system to have a latency of less than 0.5 seconds.

Figure 3: Topographic view of rover vehicle path..Click to Enlarge

Figure 3 shows that radio coverage was excellent within a 100-meter range. The position of the stationary local vehicle is near the middle right of the figure (black dot). The thin blue line is the actual trajectory of the rover vehicle, and the green dots are the perceived positions. Areas where the blue line is not covered resulted from communications interference from large obstacles. This demonstrates the line-of-sight nature of the short-range radios. Note that the communication gaps occurred more than 100 meters from the origin of the grid.

The following three figures show two interesting test cases. The figures compare results from two combinations: a stationary local vehicle with a rover vehicle and both vehicles moving. Figure 4 shows that the computed position errors of the rover vehicle as perceived by the stationary local vehicle were less than 2 meters. (Selective Availability (SA) had been turned off prior to these tests.) The graphs show that the errors were very small when the rover vehicle was stationary (flat line), but larger when it was in motion. This error can be attributed to position update latency.

Figure 4: Geodetic position error of the moving vehicle..Click to Enlarge

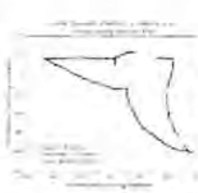

Figure 5: Local geodetic position of the local vehicle (red) ..Click to Enlarge

In the second test, both the local and rover vehicles were in motion. Figure 5 shows the paths of the two vehicles and Figure 6 shows the local geodetic position errors of the rover vehicle as perceived by the moving local vehicle. As can be seen, the longitude and latitude errors do not exceed 60.5 meters. The vertical error never exceeds 60.1 meters because the relative rate of change of the horizontal position, vertical position, and latency from one vehicle to the other is not as significant in the vertical direction. The results indicate that the moving local vehicle was able to perceive the position of the rover vehicle at accuracies within one meter.

Mine-Ready System

Tests of the prototypes demonstrated the feasibility of the concept of a GPS-based proximity warning system. Next, we developed a system that could be tested on mining equipment. This required ruggedized radio equipment and computing platforms. To run the PWS software we chose a computer used in existing equipment dispatch and control systems - namely, a ruggedized, 586-based system that runs Windows CE and has an integrated, single-frequency, eight-channel, differential GPS receiver. The computer also has serial and CAN bus interfaces. The 900-MHz IP radio and GPS antenna were also off-the-shelf products and built for agricultural and mining applications.

We used a base station consisting of a dual-frequency, RTK, GPS receiver, and another 900-MHz IP radio to distribute Compact Measurement Record (CMR) differential correction messages. We configured the GPS receiver internal to the computer to receive the CMR correction broadcast to provide corrected location outputs to the PWS software.

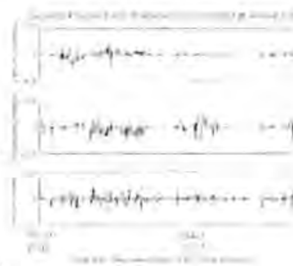
Figure 6: Geodetic position error of the local vehicle..Click to Enlarge

The mine-ready PWS operates in a manner similar to the prototype system, with a few modifications. As before, the system uses GPS to determine the location of the vehicle or mining equipment on which a system is mounted. The PWS also receives differential correction information from the base station. The IP radio then transmits the corrected location of that vehicle once per second to all other vehicles equipped with a PWS in the area. The IP radio also receives the locations of other vehicles, and the computer displays them on the monitor if they are within a specified preset range. We added to the new system the ability to show the location of stationary obstacles - such as dump points, power lines, and mine buildings - by entering their coordinates into the obstacle database.

PWS mounted on a haul truck (left) and a dozer (right).

On-site Tests. For tests at the Phelps Dodge Morenci copper mine, we installed a complete PWS on each of the following pieces of equipment: a 360-ton-capacity haul truck, rubber-tire dozer (see photo), and two service trucks (pickups). installed the base station on a nearby hill to provide differential correction information to the individual systems on the vehicles. The PWS ran in parallel to the existing real-time kinematic (RTK), differential GPS network in the mine.

We mounted the GPS antennas and IP radios temporarily, but securely, on the mining equipment and service trucks in typical locations - usually on or near the cab roof. We mounted the computer securely in each vehicle in a fashion similar to a final, permanent installation. The PWS software ran on this computer and displayed a screen for the equipment operator that showed 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 (see photo). Each vehicle's warning and detection zones could be adjusted according to the vehicle's size.

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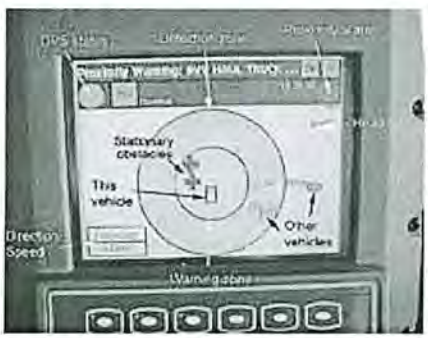

PWS computer and display

We mounted the display in Figure 8 in the haul truck and had a 30-meter-radius warning zone and a 60-meter-radius detection zone.

Alarm Levels. We set the zones for the dozer and service trucks at 20 and 40 meters. The system generated audible alarms 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. When a vehicle or object entered the detection zone, the system gave a short audible warning to indicate that it was detected. If a vehicle or object entered the warning zone, a more emphatic warning was given to indicate a possible collision.

We held the demonstration and tests in an active area of the mine where production traffic was at a minimum. The test area consisted of a simulated loading area at the bottom of a small pit, a haul road, a dump area, and a large open flat area. We repeated a truck loading and dumping cycle several times while the dozer and service trucks moved in and out of the truck's detection area to evaluate the reliability of the system.

Each system successfully tracked three other mobile vehicles and six stationary obstacles. The expected accuracy of the position of a vehicle or obstacle shown on the PWS display was 2–5 meters using the computer's internal receiver with CMR, code-phase, differential correction. Actual accuracy depends on many factors, including satellite positions (positional dilution of precision, or PDOP), multipath interference, and the type of GPS receiver used, to name a few. During the tests, we observed an accuracy of 2 to 3 meters. Higher position accuracies could be obtained using a higher quality external GPS receiver, such as the one used with the prototype system.

Multipath. One instance of multipath interference caused an error in vehicle location during preliminary tests. A service truck location was briefly shifted by 15 meters on the haul truck's screen. This was corrected as soon as the vehicle moved. However, we may need to study methods to reduce multipath problems, including improved antenna designs and mounting locations. We did not see any other multipath errors during the demonstration, and good location solutions were obtained even when a smaller vehicle was parked immediately next to the haul truck.

This was possible because the number of satellites visible to a vehicle never dropped below four, even when a larger vehicle blocked some of the satellites. This may change at different mine locations or different times of day because the visible satellite constellation depends on these two factors.

Satellite Visibility. We did not detect any problems with satellite visibility in the test area due to mine structures such as pit walls; however, in deep pits this may be an issue. Pseudolites (ground-based transmitters that simulate satellites) are being tested in another area of the Phelps Dodge Morenci Mine to supplement satellite coverage for GPS-assisted drilling equipment. The use of pseudolites in any mine would increase the number of range transmissions used to calculate position, thereby increasing the accuracy and reliability of a PWS or any other system using GPS. We would need to modify the PWS demonstrated at the mine to allow the use of pseudolites or other augmentation technologies.

We saw some problems that involved the other vehicle icons occasionally and briefly shifting position by a few meters on the haul truck's display when the truck was moving. Slight errors in vehicle heading contributed to these position shifts. The PWS software calculated vehicle heading by comparing the current position solution with the previous one, without any filtering. Any small error in position caused errors in the calculated heading. This could be remedied by integrating dead-reckoning methods and better algorithms for determining heading. Future systems will incorporate these improvements.

Future Developments

Full effectiveness of a mine-wide, GPS-based PWS would require outfitting all vehicles and mining equipment on the mine property with a system. The 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/display. Such a system could use an existing 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. The system would generate a simple audible warning 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 required to allow the operator to locate and identify nearby vehicles and objects. The PWS could stand alone like the system described here, or it could be integrated into existing dispatch and control systems.

Complete Protection. Clearly, these tests lacked a system to protect a worker on the ground. This would require a personal PWS consisting of miniature GPS equipment, a small processor, and IP radio equipment. The system would need to fit on the belt or in the vest pocket of a worker. Hardware for a personal system is available, and plans call for software development to begin next year at NIOSH.

Implementation of a GPS-based PWS now would require some method of redundancy to ensure that the equipment, smaller vehicles, and workers were protected 100 percent of the time, regardless of satellite visibility. Existing technology, such as cameras, radar, or a radio-frequency identification (RFID) tag system, also have limitations when used alone. A combination of a GPS-based system and one of these other technologies would, however, provide the redundancy needed for a highly reliable system.

Conclusions

Tests of a GPS-based proximity warning system for surface mining equipment showed that the system has the potential to reduce accidents involving collisions or driving over an edge at mining operations. Future work will involve larger- scale and longer-term tests to prove this technology adequately. Also, the proximity warning algorithms require several improvements, such as the integration of additional sensor inputs and the ability to use pseudolite signals

to increase reliability. GPS technology can assist in making the operation of haulage equipment safer, but it is only a part of an overall safety plan that includes training, safe operating procedures, and methods to monitor blind areas.

Acknowledgements

The authors would like to acknowledge the assistance of Alain Samaha, Trimble, Sunnyvale, California, in the development of this system. The initial prototype work for the system involved Thom Morley of Trimble and Glenn MacGougan, formerly of Trimble and currently at the University of Calgary. Also, the assistance of Jim Hanson, Phelps Dodge Morenci, Inc., Morenci, AZ, and Nathan Lowe, National Institute for Occupational Safety and Health, was critical to the planning and execution of the tests at the mine site. Finally, the authors would like to thank the Phelps Dodge Morenci Corporation for supporting and hosting the demonstrations. Portions of this article were based on the paper "GPS-based Proximity Warning System for Mining and Construction Equipment" by T. Holden and T. Ruff presented at the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation, ION GPS 2001, Salt Lake City, UT, September 11–14, 2001.

Manufacturers

To build each PWS tested at the mine we used Trimble equipment. This included an SG178 ruggedized computer/display; an integrated, single-frequency, eight-channel GPS receiver - specifically, a Lassen SK II OEM board with machine-control software; a GPS antenna; an external audible alarm; and a SiteNet 900 IP radio. The base station used in the mine demonstration incorporated an MS750, dual-frequency, RTK GPS receiver with a SiteNet 900 IP radio. The original prototype system utilized Trimble Ag132, single-frequency, differential GPS receivers with the Coast Guard beacon option. The wireless LAN cards (PC4800, PCMCIA type II) in the laptop computers were manufactured by Aironet/Cisco and used the IEEE 802.11b standard. They were capable of operating at 1 to 11 Mbps and were configured and tested in both ad hoc and infrastructure modes. Phelps Dodge Morenci and Empire Machinery provided the various demonstration vehicles, including the Caterpillar 797 haul truck and the Caterpillar 824 wheel dozer. (Mention of specific products or manufacturers does not imply endorsement by NIOSH.)

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