Development of a dump edge and vehicle proximity warning system based on GPS and wireless networks to improve safety in open pit mines

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Abstract

To improve the safety of off-highway trucks in open pit mines, a dump-edge and vehicle proximity warning system that uses GPS and wireless local area networks is being developed by the Colorado School of Mines and Virginia Tech Mining Departments. Based on the proven record of GPS in dispatch systems and two years of research, field tests were carried out at operating limestone quarries and at open pit mining operations to evaluate the effectiveness of the system under rugged operating conditions. This paper describes the progress made on this National Institute for Occupational Safety and Health (NIOSH) funded project and discusses tests that were carried out at the Morenci open pit copper mine in Arizona.

Introduction

During the last decade, the Mine Safety and Health Administration (MSHA) reported a significant number of accidents related to off-highway dump trucks. Between 1990 and 2004, MSHA registered 1,303 fatal accidents. Of these, 163 (13%) were classified as off-highway ore haulage accidents. At least 23 of these fatalities occurred as a result of the collision of an off-highway truck with another object, vehicle or person in an open pit mine. In 2000 alone, 13 fatalities occurred in metal/nonmetal and open pit coal mines involving off-highway trucks, small vehicles or persons hidden from view in the blind spot off the truck.

The objective of the NIOSH-funded research project was to develop a proximity warning system using a global positioning system (GPS), wireless communications networking and three-dimensional mapping technologies to reduce the number of accidents involving off-highway trucks to improve the working conditions in open pit mining operations.

The envisioned system had to meet the following goals:

- The system should be capable of tracking the vehicle with respect to the edge of a dumpsite as well as other vehicles in real-time, warning the driver of close proximity or collision.
- The system should be user friendly and easy to understand by the driver using simple and representative computer graphics.
- The mine vehicle will be integrated with a screen monitor linked to the system's computer to give the driver a real-time picture of the vehicle with respect to its surroundings.
- The system should be submeter accurate regarding its position with respect to the safety berm and with respect to the position of other vehicles.
- The system should be capable of three-dimensional contour mapping on demand to monitor a vehicle's position with respect to the mine's geometry.
- The vehicle's position should be shared among all the operating vehicles using a wireless-radio network. This system should further be able to update the mine's geometry on demand, based on remote vehicle's coordinates.
- The system must be tested in a mining operation to check for its operability, effectiveness and operator acceptance.

System description

The development of the system involved incorporation of three state-of-the-art technologies: the GPS mobile computer

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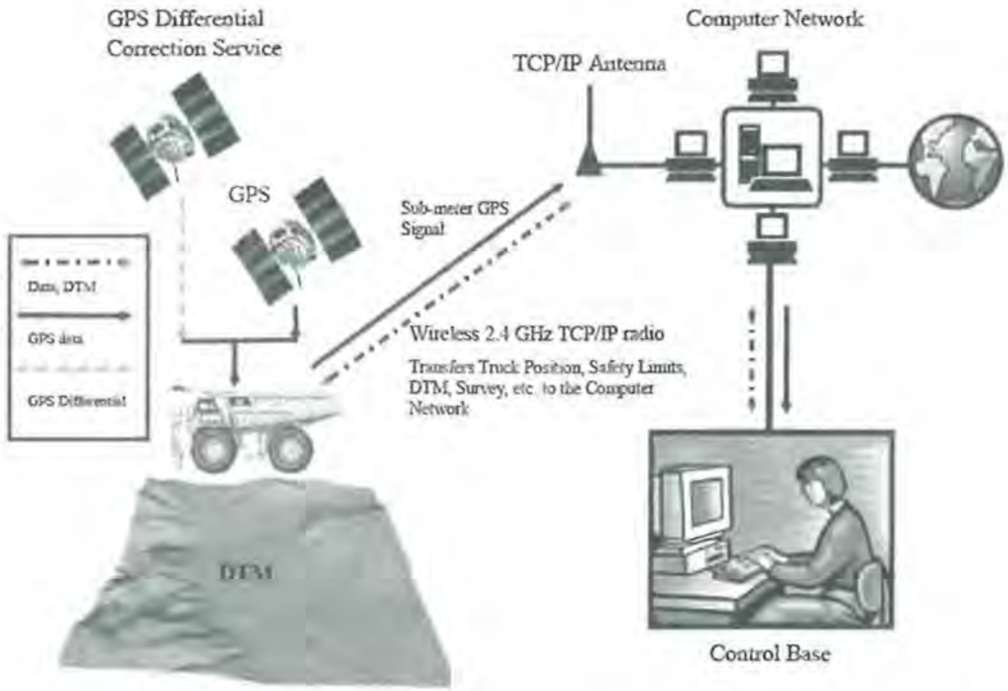

Figure 1 — Schematic representation of the configuration used to monitor a remote truck from the central office.

Figure 2 — Photograph showing the installed rugged flat panel computer in a CAT 793 truck.

system, the wireless communication network system and a three-dimensional mapping and graphical interface software system. All these technologies are combined and controlled in a real-time software system called VirtualMine.

A brief description of how the system works is as follows: As seen in Fig. 1, the system mounted in the truck cab receives the GPS signal from the GPS receiver mounted on the truck. The GPS system calculates true position by using signal correction received from the base station trough wireless radio antennas. The system calculates the position of the truck with respect to the digital terrain model (DTM), generates and updates DTMs on demand and sends this information to other trucks and to a central base station using either 900MHz or 802.11 radios. The base and vehicles receive the information in [xyz] data packets. These data packets are used to map and display the truck position on top of the DTM.

The position and terrain information is sent to the base station by way of an on-board radio in a given truck. The base station receives the data through an access point connected to a computer that is on the main wired network. If the network is routed to the Internet, the monitoring of equipment on the updated terrain maps can be carried out from any computer connected on the Internet (see Fig. 1). The same process is repeated when sending position and terrain information from vehicle to vehicle in a peer-to-peer TCP/IP scheme.

GPS and computer hardware system. The GPS system hardware is manufactured by Trimble and currently marketed by Caterpillar. The GPS receiver is configured to output the standard National Marine Electronics Association (NMEA) code, which is an ASCII readable format. The GPS unit is connected to the PC screen through a serial port. Figure 2 shows the GPS equipment installed on a Caterpillar 793 truck.

The system can track enabled vehicles within submeter accuracy using differential GPS (DGPS) or with centimeter accuracy using real-time kinematics (RTK). Both methods rely on stationary base stations to calculate GPS errors based on the difference of surveyed locations in relation to GPS readings. These base stations broadcast GPS corrections to enabled vehicles in the mine. When in RTK mode the system uses RTK-enabled receivers that are able to process the GPS carrier-phase signal to achieve centimeter accuracy. When in DGPS mode the system uses DGPS-enabled receivers to process the GPS code-phase signal resulting in submeter precision.

A tablet Xplore PC system is used as the on-board computer and display device. Xplore was selected among other similar systems because it is a rugged PC touch screen. The Xplore PC system is shown in Fig. 2.

The Xplore unit is a Pentium III PC computer based on

Windows 98 and runs at 500 MHz. It has one serial port and four USB ports. It has an internal PC card slot that can be used to install wireless radio cards.

Wireless communication system. The wireless network system used is TCP/IP compatible and it can use both, the upgraded Trimcomm radios from Trimble or standard IEEE 802.11 compatible radios.

The wireless network is used by the system to broadcast coordinates between mine vehicles in real time. These coordinates are also used by the system to generate digital terrain models (DTMs) in three dimensions on demand. Testing is being done to transmit operative data such as ore/waste, tonnage grade, truck condition and road condition.

Figure 3 is a schematic representation of the system configuration, when the vehicle is using 802.11b wireless communication protocol to send data to an internal network through a TCP/IP compatible access-point also using the 802.11b protocol. Using this configuration the vehicle can be monitored from a central office using an internal network.

The Trimble radio has two functions: to receive error correction from the base station and, because it is TCP/IP enabled, to transmit real-time data like current GPS coordinates to other TCP/IP Trimble radios.

Using Trimble TCP/IP radio configuration, the GPS receiver and the Trimble radio must be connected to the computer by way of serial and USB ports. Figure 4 describes the connection layout of the system when using Trimble radios.

Using the 802.11b TCP/IP wireless configuration as seen in Fig. 5, a USB adaptor card is used to emulate a PCMCIA card-slot to connect to the TCP wireless radio card into the Xplore computer. The signal range of standard 802.11 systems does not reach a significant distance useful for long-range communication. However, using amplifiers and omnidirectional antennas, the range can be increased to more than 3 km (2 miles).

This is an inexpensive radio system and can potentially substitute 900 MHz radio systems (see Fig. 5, which describes the connection layout of the 802.11b radios). Two vehicles, a Caterpillar 793 truck and a Chevrolet pickup truck, were equipped with the VirtualMine system (described below) using 802.11b radio cards with one-watt amplifiers and connected to omnidirectional antennas.

Virtual mine software. Development of the virtual mine software and its visual graphical interface was carried out using visual-basic language. The software helps to perform the following functional areas:

- reading and extracting NMEA code coming from the GPS unit,
- converting NMEA code from its original geodetic format into universal coordinates (UTMs).

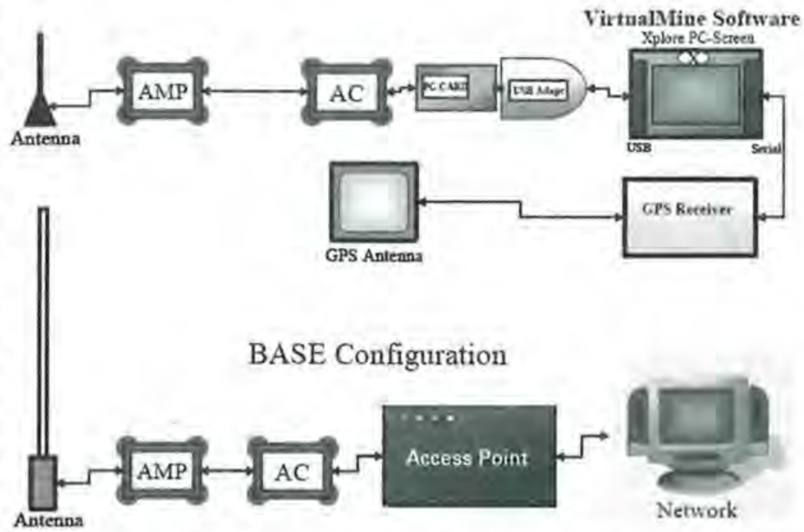

Figure 3 — Schematic representation of hardware configuration for truck and access point.

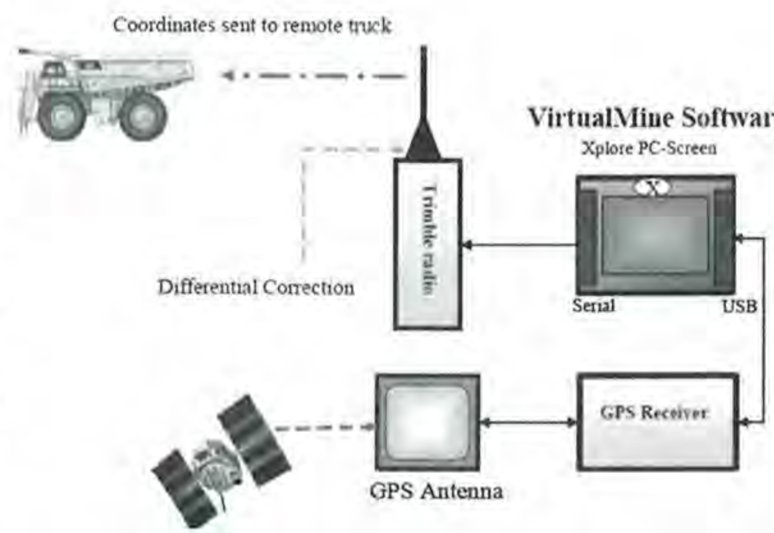

Figure 4 — Schematic representation of the system using Trimble radio system.

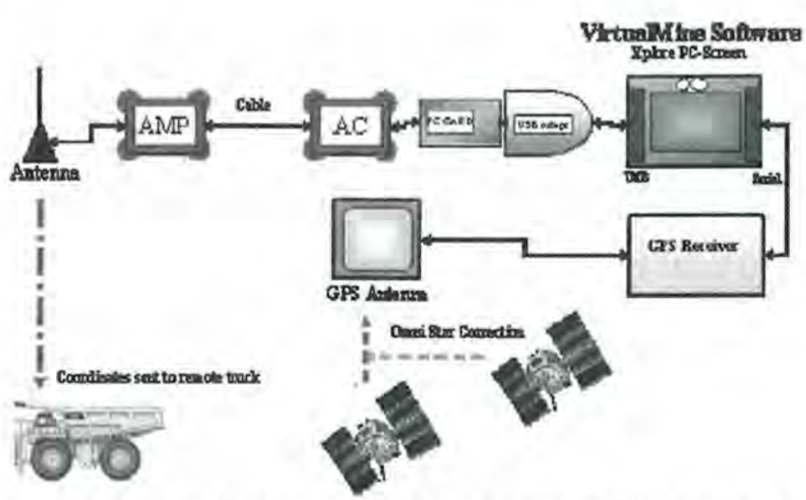

Figure 5 — Schematic representation of the virtual-reality wireless radio communication system using 802.11b protocol with one-Watt amplifiers.

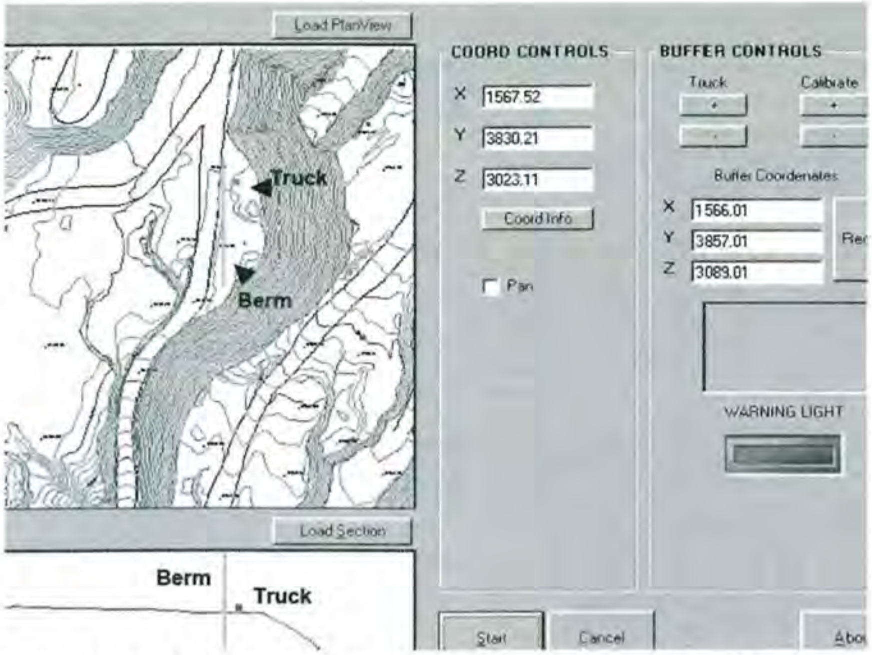

Figure 6 — A warning sound and a flash signal are activated as the truck approaches the virtual safety berm.

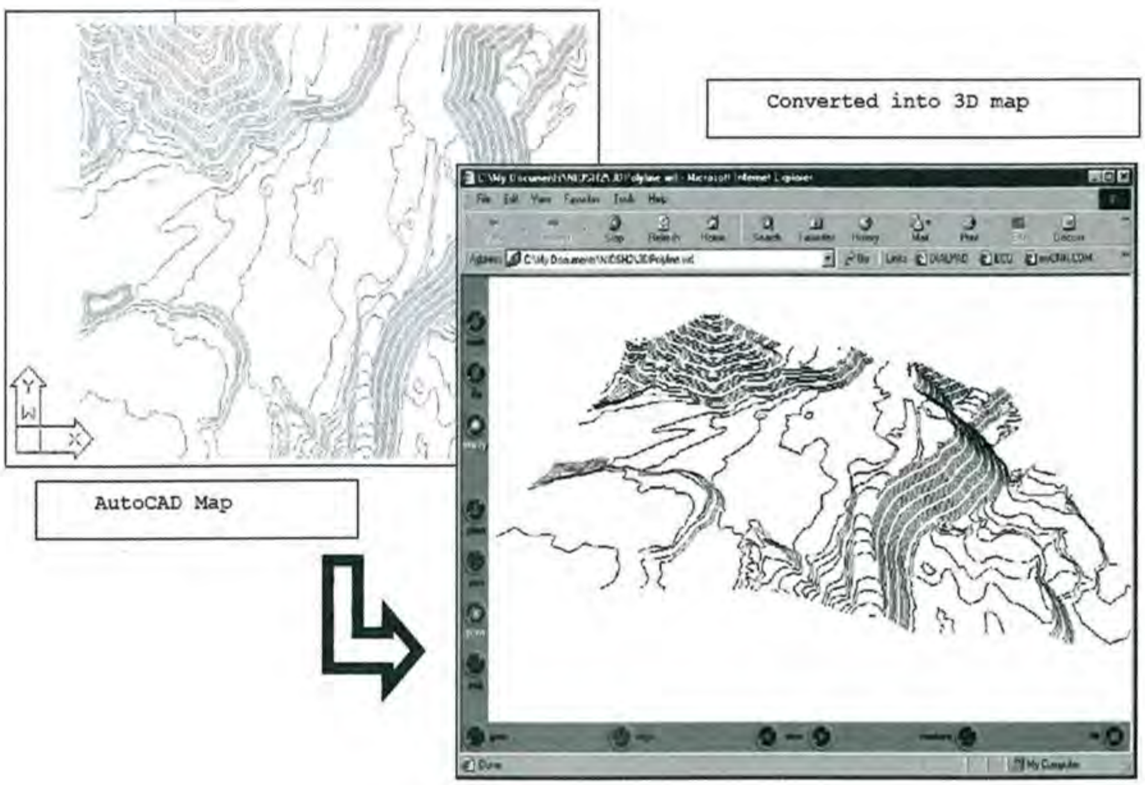

Figure 7 — Representation of the conversion process from a DXF (AutoCAD map) into a three-dimensional map (VRML map).

- transforming AutoCAD mine maps into three-dimensional dynamic mine models,
- visualizing three-dimensional mine models,
- tracking positions of local and remote vehicles in real-time,
- handling TCP/IP wireless communication protocol to transmit and receive positional and terrain data from remote vehicles,
- generating three-dimensional mine maps on-demand and
- providing proximity warning to vehicles and to prespecified locations within the mine.

Initial software development based on a two-dimensional graphical user interface

The initial approach followed for displaying a vehicle over a map was to develop an algorithm written in Visual-Basic to read and interpret vehicle coordinates coming from the GPS receiver to display the truck over a plan view imported from a AutoCAD DXF mine map. DXF stands for drawing exchange format. This nomenclature was first used AutoCAD to support drawing file translation to and from other mapping or drawing software packages.

The system user loads the DXF map of the mine and defines proximity zones such as a dump point. Once the GPS unit is activated, the system starts tracking the vehicle position with respect to the dump point over the map. A series of visual and audio alarms are activated by the system to warn the driver of proximity to the dump point.

The dump point is defined at a certain distance with respect to a safety line (vertical straight line in the center of the map in Fig. 6) that is seen as a "digital" safety berm to the dump's edge.

The software code receives the position of the truck given by the GPS system and displays this position on previously uploaded DXF top map of the dumpsite. The location of the safety berm is also displayed with respect to the edge of the dump.

The two-dimensional system is designed such that two separate views of the dumpsite are generated in the graphical interface: the plan-view on the top part of the screen and the equivalent section-view just beneath (Fig. 6). Using this format the driver can track at the same time, his vertical position as well as his horizontal position with respect to the dumpsite edge. The mine geometry as well as the dump point information can be fed into the system by a radio link. The program also displays a line representing a virtual safety berm. The distance between the truck and the safety berm is monitored by the system using GPS information; a warning light is activated as the truck approaches to the dumpsite. The software activates a series of visual and sound alarms as the truck approaches the virtual safety berm representing safe distance from the edge of the dump. Warning conditions can be configured dynamically accordingly to truckload, speed and soil conditions.

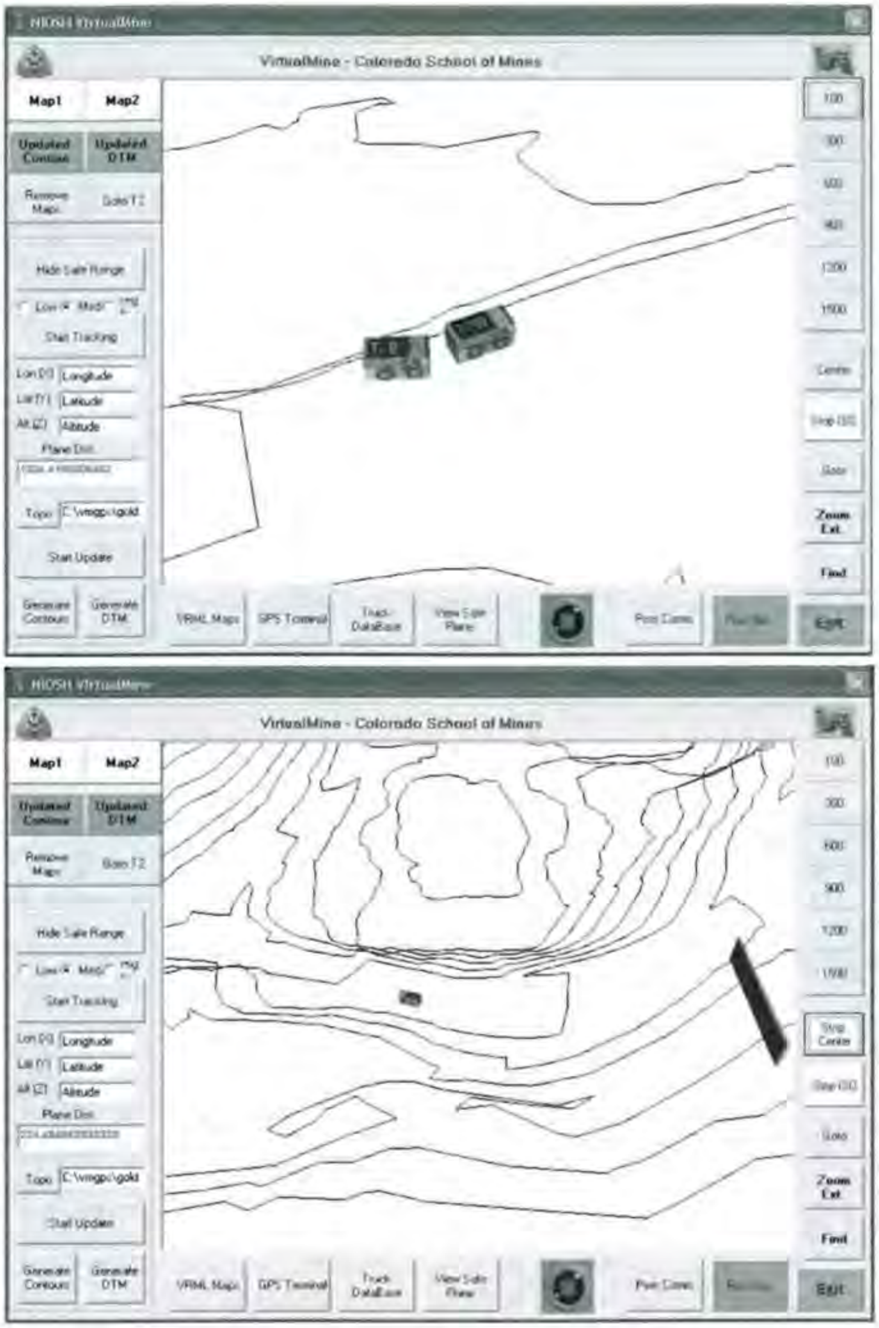

Figure 8 — Three-dimensional isometric views showing the position of trucks being monitored by VirtualMine on a given contour map.

Figure 6 shows a map-view and a section view of the dumpsite as the truck crosses the safety berm. As the operator crosses the virtual safety berm, the computer system cautions the operator with a series of audio and visual warnings.

Virtual mine software development based on a three-dimensional graphical user interface

A new three-dimensional concept was incorporated into the system. For this, a new software code was developed in visual basic utilizing virtual reality modeling langue (VRML) routines.

Because three-dimensional rendering in VRML format can be programmed using visual-basic to create and animate three-dimensional environments, the approach followed was to first create a Visual-Basic program to translate AutoCAD DXF maps based on three-dimensional contour lines or polylines into the equivalent VRML three-dimensional lines. Thus, a mine map created in AutoCAD (or DXF) can be imported to the system into a three-dimensional model instead of using digital plan-view maps or sections. Once imported, the three-dimensional mine model, the terrain model can be dynamically updated on-demand based on the three-dimensional GPS data being gathered by the equipped vehicles such as trucks and dozers.

Figure 9 — Three-dimensional safety sphere (truck inside) intersecting with the safety virtual berm (plane).

Figure 10 — Two trucks in close proximity.

The first step to translate DXF poly-lines to VRML was to code an algorithm that can open and read the DXF lines and their constructing three-dimensional points to generate the equivalent three-dimensional VRML model of the contour map.

Figure 7 is a simplified sketch of the process of translating a DXF contour map into VRML format using the VirtualMine's three-dimensional translator routine. Because VRML three-dimensional environments are web compatible, the newly translated map is displayed using an Internet browser (right). Currently the system can import DXF maps from AutoCAD R.12 or DXF maps generated by any other mapping application.

The software system generates a three-dimensional truck model, which is dynamically positioned on the map based on the XYZ coordinates coming from the GPS unit. The system then monitors the three-dimensional truck position with respect to the mine map as shown in Fig. 8.

The software can also generate a three-dimensional spherical bubble to indicate the safety zone around a given truck (Fig. 9).

The VirtualMine system can also monitor the three-dimensional truck position and the distance with respect to a virtual safety berm represented by a plane (see Fig. 10). The position of the virtual safety berm is previously fixed with respect to the edge of the dumpsite, depending on the truck characteristics and soil conditions. If the truck approaches this plane, a series of alarms are triggered to warn the operator of berm proximity. Likewise, if the vehicle approaches another equipped truck, the system will warn of truck proximity (see Figs. 9 and 10).

The VirtualMine system is capable of updating the computer three-dimensional model of the mine in an on-demand basis using the GPS information coming from the actual vehicle. By using the vehicle wireless network and by combining the GPS location coming from other trucks and vehicles, such as dozers, the system can also provide digital models covering larger areas in the same amount of time as one vehicle. This is accomplished by first saving the GPS coordinates received through the wireless network to generate a grid file. This three-dimensional grid is automatically contoured and displayed on-demand on the onboard computer screen (see Fig. 11).

Another feature of the VirtualMine system, in addition to sending and receiving data, is to query the data coming from the network of enabled vehicles. Once the data generated in the operation is centralized into a single location, operational data can be analyzed or queried as seen in Fig. 12.

Field tests

Various tests were carried out at the Morenci open pit copper mine, Morenci, Arizona, to check the applicability of the system. Once vehicle instrumentation and system configuration were completed, two tasks were performed: vehicle tracking and contouring.

On-demand mine surveying and contouring. Mine surveying and vehicle proximity tasks were carried out in real-time using two vehicles, a pickup truck and a CAT 797 truck (see Fig. 13).

To run these tests at the mine site, the mine model was generated and imported into the VirtualMine system by transforming

AutoCAD digital maps, which were based on local state coordinates into VirtualMine universal coordinates.

Once the mine model was transformed into UTM WS-84 coordinates, the GPS location of the truck reported by the system was compared with the actual location of the truck in the mine to check for GPS location vs. Mine Model reliability. The on-demand contouring task consisted of driving to the main pit to generate and store GPS terrain data to eventually generate and update the mine model. This task confirmed accuracy of GPS vehicle positioning with respect to the already loaded model of the mine.

Generation from scratch of a pit model using new GPS data was carried out. The system was able to update the pit three-dimensional model and generate contour maps on demand by driving the vehicle within the pit. In Figs.14 and 15, one can see the real pit at Morenci and the equivalent three-dimensional contour map as seen through the VirtualMine interface. Note the location of the CAT 793 truck in both pictures.

Figure 11 — Three-dimensional contour map generated on-demand by driving at the CSM campus.

Vehicle proximity warning test. A vehicle proximity warning feature is incorporated in VirtualMine by using the GPS location already generated and transmitted by enabled vehicles within the system wireless network. The system uses the GPS data generated in each vehicle to display vehicle location in the onboard computer three-dimensional model. Based on a predefined minimum safety distance and the GPS location, the system calculates separation distances between vehicles and activates a series of alarms if critical proximity is detected.

As mentioned, the VirtualMine system was installed in a CAT 793 truck and in a pickup truck to test vehicle proximity. Figure 16 is a photograph taken from the pickup truck and shows the 793 truck in front of the pickup as both vehicles are driving forward within the mine. Inside the pickup truck, the system interface is showing both vehicles moving in relation to the digital model version of the mine, within a safety distance range as indicated by the safety bubble surrounding the pickup truck.

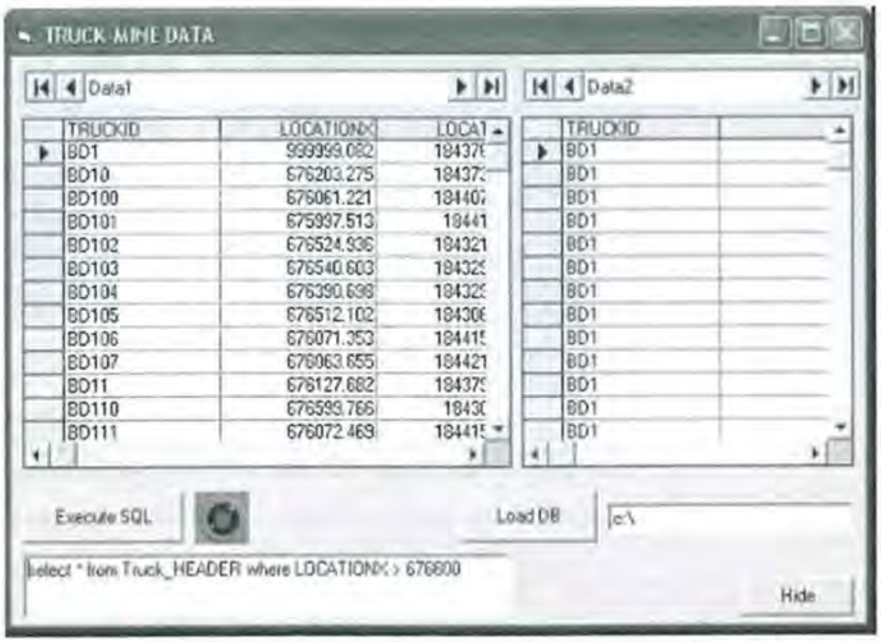

Figure 12 — Database interface used to transmit and receive data from central office to the truck.

Dump edge contouring and proximity warning tests. This test was carried out by emulating a dozer pushing material over the dump's edge using a pickup truck "acting" as a dozer and performing the equivalent movements of a dozer as if is pushing material over the dump's edge. During this process, the 793 truck is on hold receiving GPS terrain data from the "acting dozer" as it moves back and forth. The objective is to emulate the formation of a new dump edge as fresh material is being dumped by the dozer.

As the dozer keeps moving material, The 793 truck is receiving new terrain data from the dozer and keeps updating its mine terrain model. Once the dozer is done, the 793 truck system has already incorporated the new terrain data received from the dozer and generates a new terrain map of the dumpsite as seen in Fig. 17, the truck is then ready to move into the dumpsite based on the new terrain profile.

As the truck backs into the edge of the waste dump, as seen in Fig. 18, its location is immediately shown on the new map displayed by the truck's computer screen, as shown in Fig. 17.

Figure 13 — Photograph of the truck and pickup used in testing the system.

Figure 14 — Photograph of the main pit at Morenci (2002).

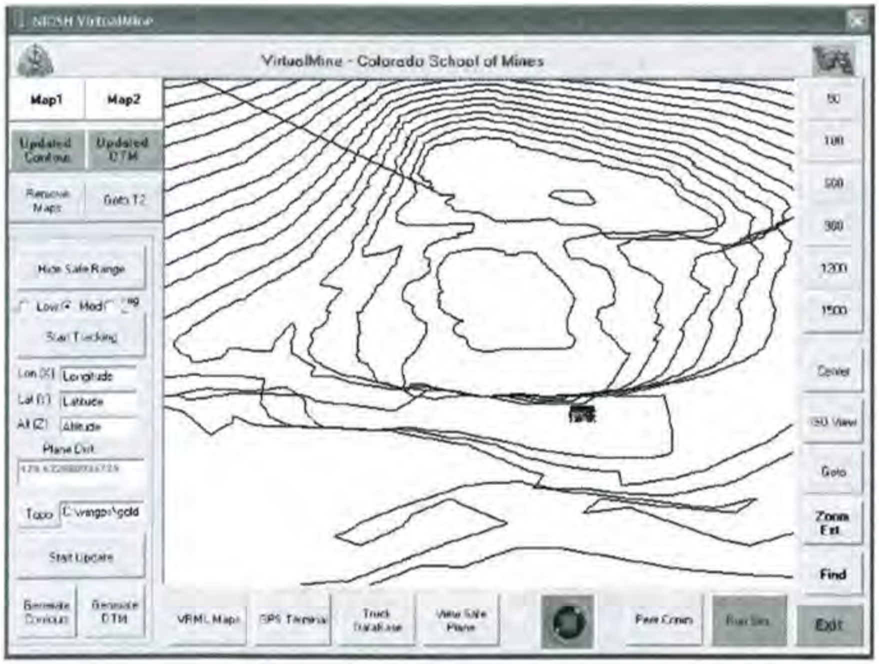

Figure 15 — Virtual equivalent of the main pit at Morenci as seen in VirtualMine.

A series of field tests were carried out to check the accuracy of the GPS receivers used in the VirtualMine system.

In one of the tests (as shown in Fig. 19) the actual positions of the vehicles were compared to the vehicle locations given by the VirtualMine GPS system. In Fig. 19 (a), the actual distance between vehicles is measured based on the distance between the GPS antennas mounted on the vehicles. Figure 19 (b) shows in VirtualMine the equivalent calculated distance between the simulated trucks. The registered GPS locations of each truck vs. their real location in the mine during the proximity warning tests validated the submeter accuracy predicted to be achieved by this system.

Conclusions and recommendations

Fatal accidents related to dumping tasks and vehicle collisions are occurring at open pit mines. The VirtualMine system developed in this project can help to improve safety in open pit mines and could reduce a number of these accidents.

The system tests that were carried out at the Colorado School of Mines and in actual mining operations such as the Morenci mine in Morenci, Arizona, indicated that "VirtualMine" is a system that can be used as a vehicle tracking, proximity and collision warning system. However, the system being developed has to be rigorously tested at open pit mine sites to check its reliability and effectiveness.

Further research is recommended to continue developing this system into a mine expert system within the following scope:

- dispatching systems,
- optimizing shovel operations (two sides loading),
- real-time mine planning and control and
- interface for driverless systems.

Figure 16 — Photograph taken at Morenci during the proximity warning test.

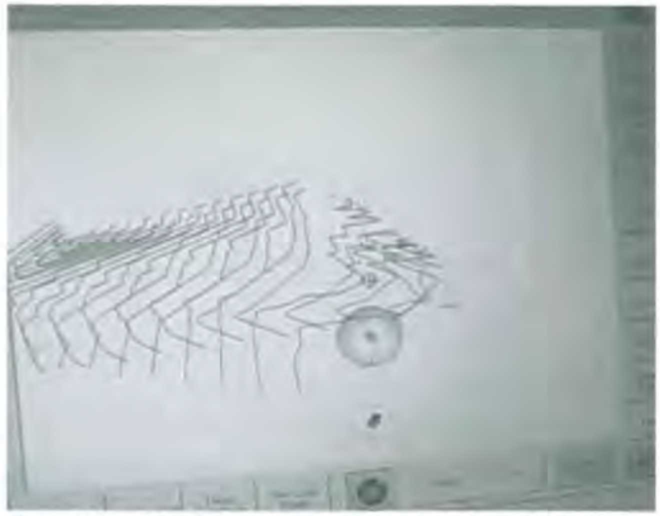

Figure 17 — Computer screen mounted at the mine truck showing its position during dumping over the updated map.

Figure 18 — The mine truck during the dumping process based on the new updated map that was radio transmitted from the dozer.

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Figure 19 — Checking consistency between VirtualMine models and the vehicles on the actual field.

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