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# An adaptive, run-time navigation system for haul trucks in surface mines

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**ABSTRACT**

This paper presents a navigation system for haul trucks in surface mining. The main features of this system include the following: (1) realistic earth-view maps; (2) run-time customisation of the maps; and a (3) unified graphical user interface (GUI). The system implementation comprised of three parts: map pre-processing, sensor communication system and unified GUI development. Map pre-processing involved development of a new method for incorporating accurate earth-view maps in the navigation system for a frequently updating environment like surface mines. An IEEE 802.11b wireless network in *ad hoc* mode was used to achieve communication between sensors (global position system (GPS), proximity) and vehicles. A unified GUI was developed to display the data acquired from different sensors on the customised maps. The GUI also features a dynamic layering tool for run-time customisation of maps. This tool generates custom warnings based on the changed environmental, geographical conditions or hazards. The prototype of the system was deployed in a surface coal mine in the southern United States. Result of the testing showed that the GUI was able to accurately display the GPS data on the earth-view map developed using the map pre-processing method. The sensor system used for the zone-based proximity warning was able to identify correct zone 90% of the time and about 10% times, the zones were classified as the directly neighbouring zone. Thus, the initial testing proved that the system was feasible and is expected to improve the users' awareness of their surroundings and overall safety.

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Navigation; proximity; GPS; Ad hoc network; earth-view maps

## 1. Introduction

Although the total number of mining fatalities has shown a decreasing trend in the last two decades, the fatalities involving mining equipment remained unchanged. According to the Mine Safety and Health Administration [1], a total of 701 mining-equipment-related fatalities were observed in the United States between 1995 and 2014. Annual equipment-related fatalities were 37–88% of all mining fatalities from 1995 to 2005 [2]. A significant number of these fatalities were related to haul trucks (~22.3%). Obstructed vision and lack of awareness of the surrounding environment, caused by the

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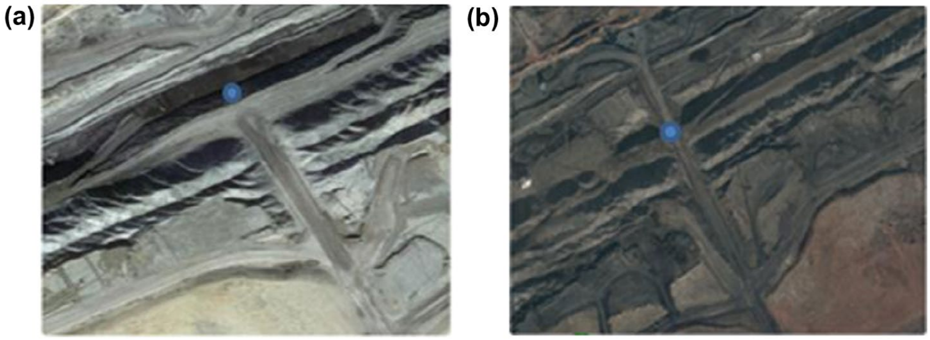


**Figure 1.** Challenges associated with implementing earth-view maps in the GPS: (a) map obtained from the Google earth map data source; (b) map of the same region as (a) obtained using custom aerial imagery.
Note: Blue dot represent same geographical location.

massive size and large blind spots of these vehicles, are some of the contributing factors in haul truck-related accidents [3]. To mitigate the root causes of haul truck accidents, both traditional approaches (safety regulations, training and education and engineering of the work environment) and innovative approaches (sensor-based technologies) have been proposed in a previous study [4].

Innovative approaches rely on electronic, sensor-based technologies that provide warning/cues to the operators to improve their awareness of nearby obstacles. Global position system (GPS) is probably the most common sensor-based system used in surface mines. The GPS establishes the position of vehicles (with sensors) in a mine with an accuracy of 3–4 m. The current applications of GPS in surface mines are mostly tailored to fleet management activities such as real-time equipment tracking and material tracking [5,6]. The graphical user interfaces (GUI) used in fleet management implements simplistic maps/line diagrams to represent relative vehicle position and path information. Such maps/diagrams and the GUI may meet the needs of fleet/productivity management systems, but underutilise the true navigation potential of the GPS.

In this paper, a navigation system for haul truck drivers in surface mine is presented. The key features of this system include: GUI with realistic earth-view maps; run-time customisation of maps; and unified GUI that integrates GPS and other proximity system data.

A GUI with the ability to integrate realistic earth-view maps with GPS sensor data has the potential to enhance users' situation awareness and improve overall safety. Realistic earth-view map is defined as a true map that shows recent geographical developments on an earth view. Integration of earth-view maps into surface mine navigation systems is challenging due to the limited availability of map data sources. There are only a few map data sources, including Google Earth (GE) maps and Bing Aerial maps. Maps in these databases are updated every 1–3 years [7]. For a typical surface mine, maps change on a regular basis depending upon the excavation plan. Figure 1(a) and (b) shows a map obtained from the Google database and a true map obtained using custom aerial imagery, respectively. The true map shows recent geographical developments that are completely missing from the Google map. To handle the lack of accurate and updated maps for surface mines, we have developed a map pre-processing method. This method integrates online servers maps (typically obtained from Bing, Mapnik, OpenCycleMap, etc.) with true maps (typically obtained using aerial survey, satellite imagery, AutoCAD drawings, etc.) and facilitates standard GUI navigation functions, such as translation, rotation and zooming.

The mine environment also exhibits conditions that often change quite frequently, even several times a day. For example, there may be paths that have become temporarily inaccessible or a road that has become slippery and therefore hazardous to access. We incorporated dynamic map layering, which allows run-time customisation of maps and therefore provides updated geographical information to users. A mobile ad hoc network or central server over an intranet can be used to transmit such information to the vehicles.

A zone-based proximity warning system based on GPS and radio frequency (RF) sensor system is integrated into the navigation system. Proximity warnings alert users when they are in close range with other vehicles/equipment. Unified GUI present GPS and proximity information on the same screen and eliminates the need to switch between multiple screens to look for hazard warnings.

Because of their importance in improving safety, navigation systems have been previously integrated in surface mines. One such system was the assisted driving system (ADS) proposed by Sun and Nieto [8] to reduce haul truck accidents related to low visibility. This system was based on GPS, ZigBee and the GE 3D graphical engine. The GE acts as a user-friendly, powerful, 3D graphical interface. The ADS software converts the AutoCAD mine maps into GE maps and then uploads the newly converted mine maps to the system server. The map information stored in a local server is transmitted to every equipped vehicle through a wireless network. The interface allows accurate, real-time tracking of the vehicles in the mines. The system provides available exit/escape routes for haul truck operators during severe weather conditions that lead to low visibility.

Our system is different from existing surface mine navigation systems, such as ADS, in terms of the following: (1) mode of communication, (2) run-time map customisation and (3) unified GUI. The latter two were explained in the previous section. In our system, we have implemented IEEE 802.11b communication in an ad hoc mode in which vehicles broadcast their GPS data to others within their communication range. Rationale for specifically using IEEE 802.11b is discussed in previous study [9]. Ad hoc mode of communication used in our system is different from other typical GPS-based navigation system that utilises a cellular or long-range multihop network to synchronise and broadcast the data.

## 2. System implementation/evaluation

The software was written in Java and based on open source project JMapViewer [10]. The GPS scripts and the network interfaces for ad hoc communication were written in Python programming language. The hardware used in the development of the system consists of the following components:

- Motion CL920 tablet PC running Windows 7 with Intel Pentium Baytrail N3540 Quad core processor, 4 GB system memory and 64 GB system storage [11].
- GlobalSat BU-353-S4 GPS sensors [12].
- Alfa AWUS036H wireless network card with 5dBi antenna operating at 2.4 GHz under IEEE 802.11b protocol [13].
- Telosb motes with MSP430 microprocessor along with a 2.4 GHz IEEE 802.15.4 radio [14].

The implementation process consists of three major components: map pre-processing, sensor communication system and GUI (Figure 2). Each of these components is explained in the following sections.

### 2.1. Map pre-processing

A geo-tile library was used for this purpose. A geo-tile library stores the map as blocks of images, typically of $256 \times 256$ pixel dimensions. The tiles represent a geo surface when affixed to a grid. These tiles have the latitude and longitude information embedded in them for seamless integration with the data provided by the GPS sensor. Typically, the geo-tiles could be obtained from various tile servers like Google Maps, Bing Maps, OpenStreetMap, etc. [15]. We obtained the geo-tiles from Mapnik server.

The tiles follow a spherical Mercator (EPSG 3857) projection standard. This projection standard employs an elliptical projection scheme and ensures that the latitude and longitude of the locations are between −20,037,508.34 and 20,037,508.34. The tiles, when acquired from the tile server, follow a

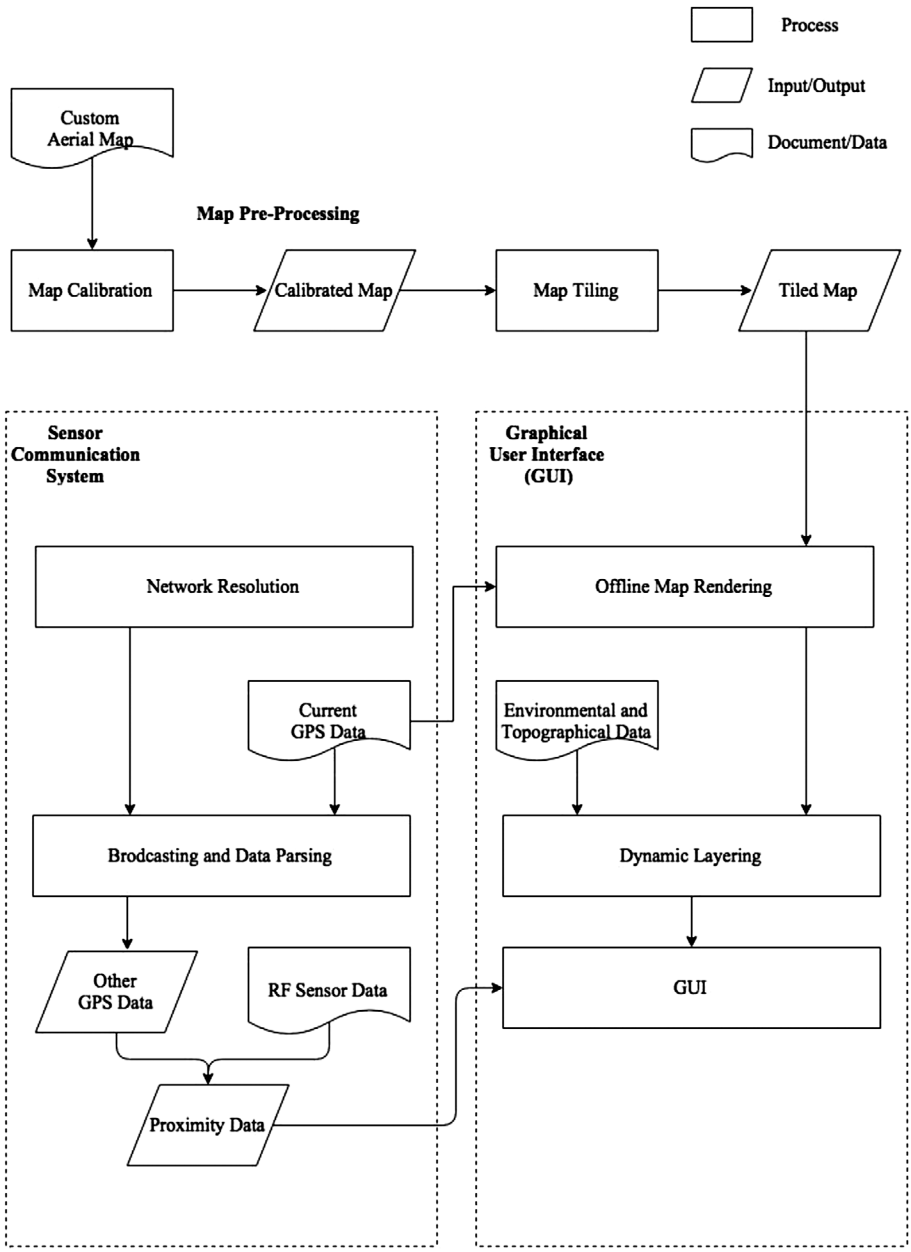


**Figure 2.** Working process flowchart for the navigation system.

streamlined local file structure: first parameter in the file path refers to the zoom level, and the next two parameters indicate the subdirectories for the x and y indices of the grid, respectively.

This local file structure facilitates an efficient encoding mechanism for indexing of the map tiles when queried for displaying in the GUI. The following Equations (i.e. (1) and (2)) represent the relationship between the latitude and longitude data provided by the GPS sensor and the tile and zoom levels used by the local file structure:

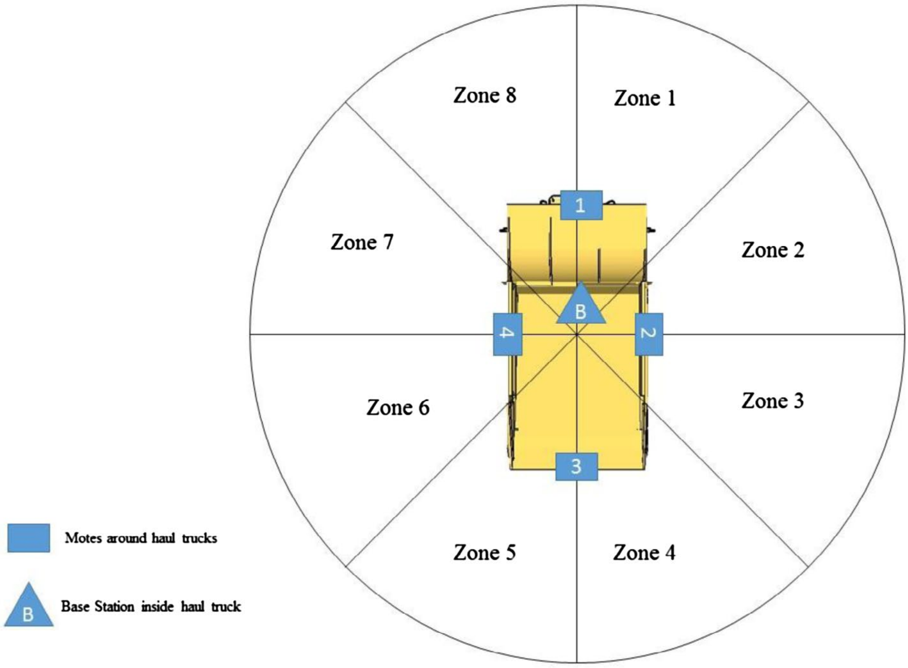


**Figure 3.** Illustration of mote deployment and zones surrounding a haul truck.

For $n = 2$^zoom.

$$\text{Xtile} = n * \left(\left(\text{lon\_deg} + 180\right)/360\right) \tag{1}$$

$$\text{Ytile} = n * \left(1 - \left(\log\left(\tan\left(\text{lat\_rad}\right) + \sec\left(\text{lat\_rad}\right)\right)/\pi\right)\right)/2 \tag{2}$$

where $n$ is two power of zooming value, XTile is $X$ tile index in the grid after rounding, YTile is $Y$ tile index in the grid after rounding, lon_deg is longitude value in degree obtained from the GPS sensor, and lat_rad is latitude value in radians obtained from the GPS sensor.

Once the geo-tile library is established, the next step is matching the tiles using an accurate and most updated earth-view map. The proposed system was developed in collaboration with a surface coal mine in the southern United States. The earth-view map was provided by mine management. They obtained the map through routing aerial survey, which is typically of $12580 \times 9939$ resolution. The calibration of the earth-view map with the geo-tile library is a crucial step. Any error at this point may result in an inaccurate presentation of GPS data within the GUI panel. To minimise such error, the boundary of the custom earth-view map was matched in AutoCAD using the exact latitude and longitude values. Additionally, pointers (~45) were created to accurately orient and align the earth-view map with the geo-tile map.

Map tiling software was used to accurately tile the earth-view map. The tiling software creates $x$ and $y$ tiles for different zoom levels that match with the tiles present in the existing geo-tile library. The tiles were organised in the navigation system directory so that local file structure similar to the geo-tile library was established. This was done to facilitate presentation of the earth-view tiles within the GUI using similar query Equations (i.e. (1) and (2)).

### 2.2. Sensor communication system

To facilitate communication between the vehicles (where each vehicle is equipped with GPS sensor and tablet PC), a wireless mobile ad hoc communication network is established with the help of Alfa AWUS036H wireless network cards with 5dBi antenna operating at 2.4 GHz under IEEE 802.11b protocol. At each node (node refers to a tablet PC inside the vehicle), the data stream is broadcast using a Java class integrated into the system, and data from other nodes are obtained through listener Java class. This eliminates the need for any central server and the communication works completely offline.

In order to establish a common ad hoc network between different vehicles, the nodes were configured using identical, wireless extended-basis service set identifier (ESSID) and wireless channel identifier. An ESSID is special kind of service set identifier (SSID) that helps in identifying the network name in a wireless ad hoc network [16]. The uniqueness of vehicle identity in the communication was established with the use of IP address. Each vehicle has a unique IP address and most recent location information can be resolved using the timestamp.

The ad hoc network was designed as a safety feature to improve users' awareness of surrounding vehicles. To further augment this safety feature, a radio frequency (RF)-based proximity warning system was integrated with the navigation system. The hardware used in the proximity warning system consists of Telosb motes with MSP430 microprocessor along with a 2.4 GHz IEEE 802.15.4 radio. IEEE 802.15.4 is a wireless standard that specifies the physical and MAC layer for wireless personal area networks. Note that the popular Zigbee protocol is written on top of IEEE 802.15.4 and utilises the IEEE 802.15.4 specification. However, in our system, we have not utilised Zigbee protocol. We have only used a specific hardware called Telosb mote which is equipped with the IEEE 802.15.4 radio operating in 2.4 GHz. We have implemented send and receive on top of the raw IEEE 802.15.4 radio for data exchange between the Telosb motes. The telosb Motes were deployed on the four sides of haul truck as shown in Figure 3 and these act as zone markers. The four motes divide the truck into eight zones as shown in Figure 3.

In addition, another Telosb mote was carried by a person to move around the haul truck and it was used to evaluate the testing performance. We refer to this as mobile mote. Thus, the mobile mote represents objects of interest (equipment/small vehicles/person) around the truck that need to be detected and visualised on the GUI. The mobile mote broadcasts beacon messages through the IEEE 802.15.4 radio and these are received by the four zone marker motes. The received radio signal strength of the beacon messages at the zone marker motes was used to identify the zone in which the mobile mote is located.

### 2.3. Graphical user interface

A unified GUI was developed for the integration and meaningful presentation of the information acquired from the GPS, ad hoc network and RF system. The basic GUI was designed to make it similar in appearance and functionality with the typical GUI used in commercially available navigation systems. Based on JMapViewer, Java programming language was used to achieve GUI functionalities, such as zooming, translation and rotation of the map. These functionalities maintain a fixed and centrally located position of the primary vehicle (driven by the system user). The primary vehicle always moves forward (upwards) with respect to the environment (map, other vehicles, etc.) (Figure 4(a)). Other vehicles/people/objects position obtained through the ad hoc network and RF sensor system are depicted using markers/symbols in the same GUI (Figure 4(b) and (c)). The GUI also provides zone-based warnings when an obstacle or a remote object is in close proximity to the primary vehicle (Figure 4(d)).

To achieve run-time customisation of maps, a masking/editing tool was developed. This tool facilitates creation of custom warnings (Figure 5(b)) based on recently updated ground/road/environmental conditions. Some examples of such warnings include slippery conditions, road construction, new intersection, etc. The interface used to generate warnings with map masking is shown in Figure 5(a). For

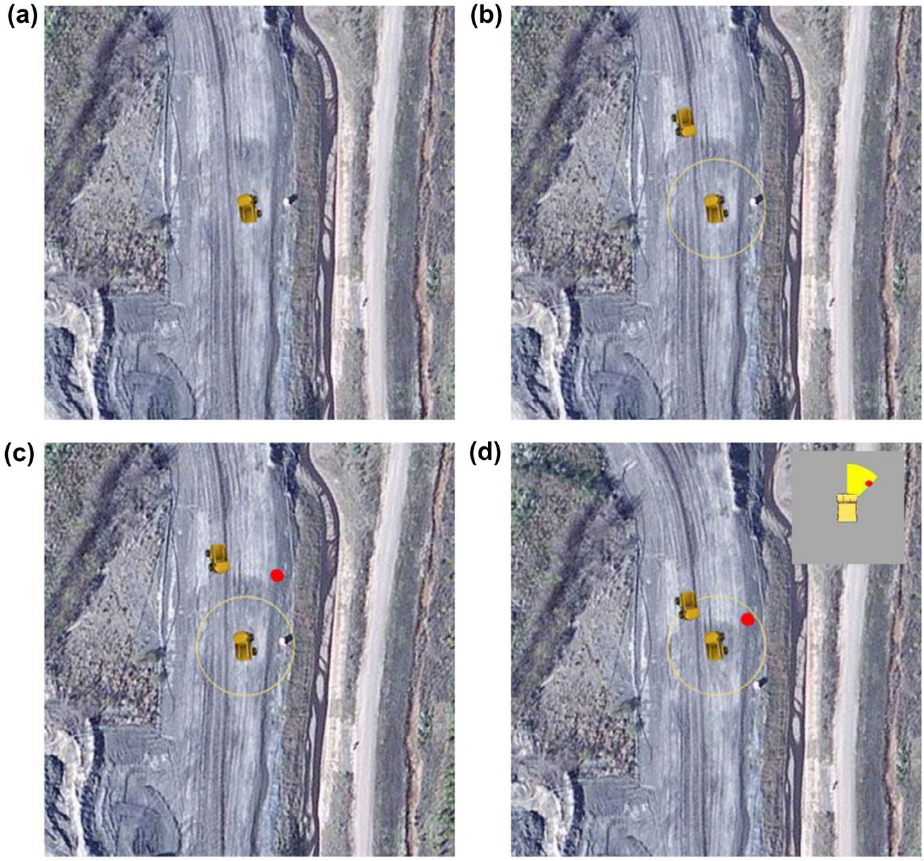


Figure 4. GUI: (a) Current vehicle location on a earth-view map; (b) other vehicle location obtained through ad hoc network on a earth-view map; (c) location of object of interest obtained through RF-based proximity system; (d) GUI with proximity warning.

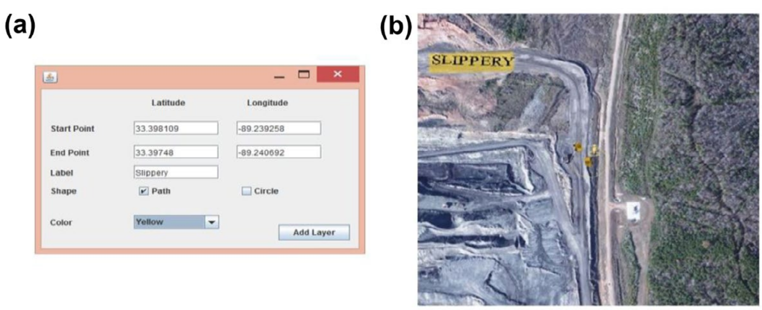


Figure 5. (a) Snapshot of special marking/editing tool for generating custom warnings (b) Snapshot of map with custom warning.

example, if the dispatcher wants to mask a certain part of the road and insert a slippery road warning, he can do that by providing the corresponding latitude and longitude information, and selecting shape and colour functions. The custom warnings are transmitted wirelessly through the ad hoc network.

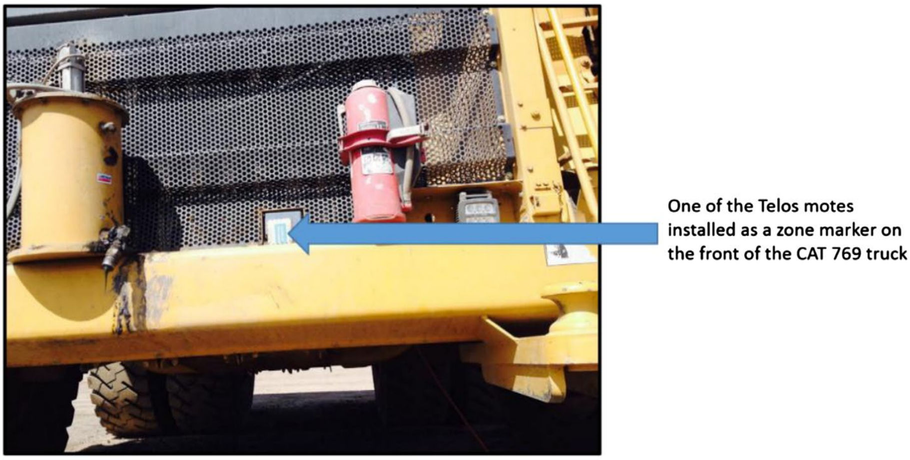


Figure 6. One of the mobile motes installed on the front of the CAT 769 truck during system testing.

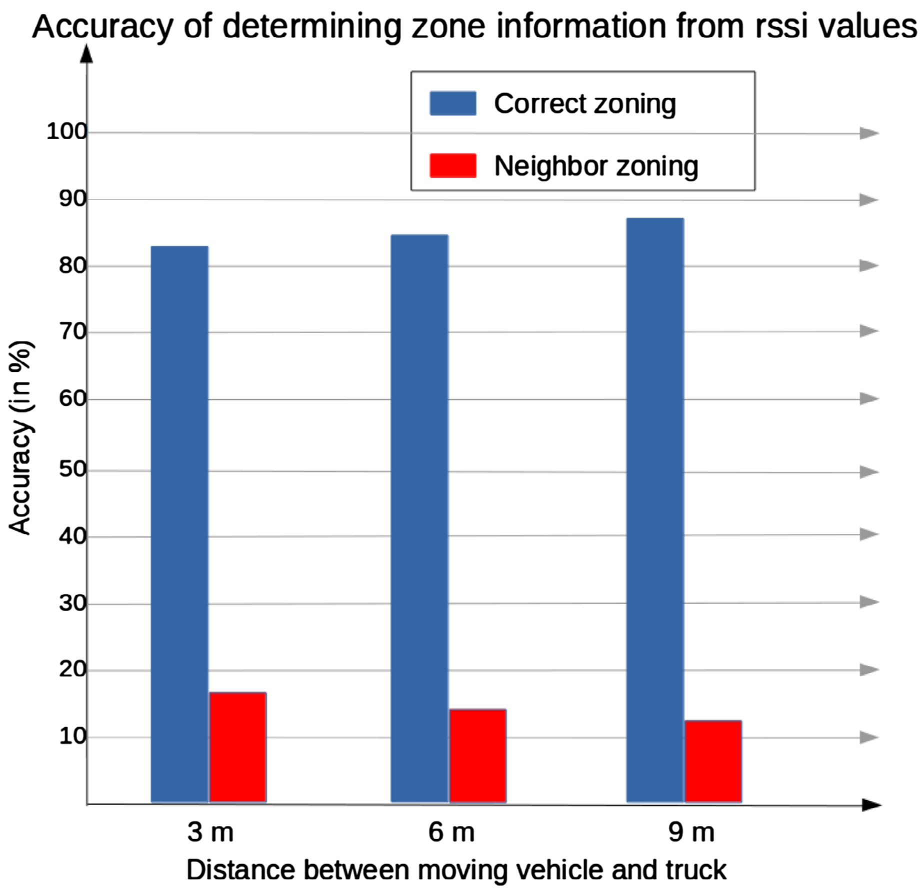


Figure 7. Accuracy of determining zone information based on RSSI values [9].

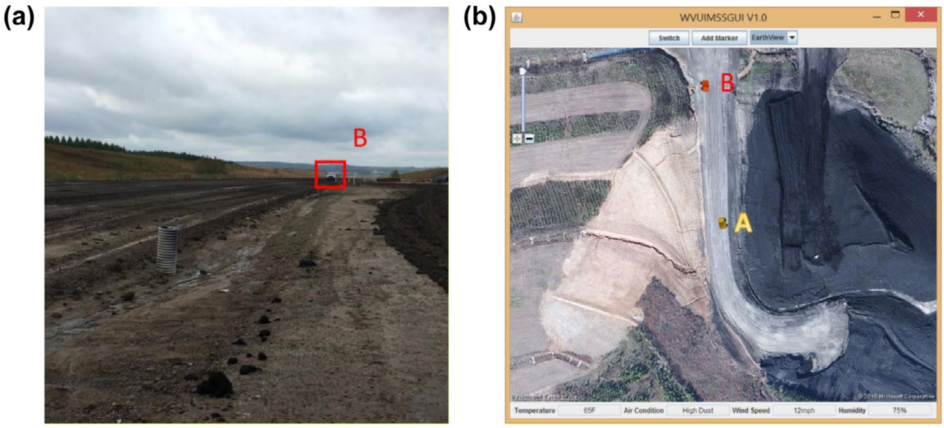


**Figure 8.** Testing of GUI with GPS data. A and B in the GUI represent primary and secondary trucks, respectively. Primary truck is not visible in (a).

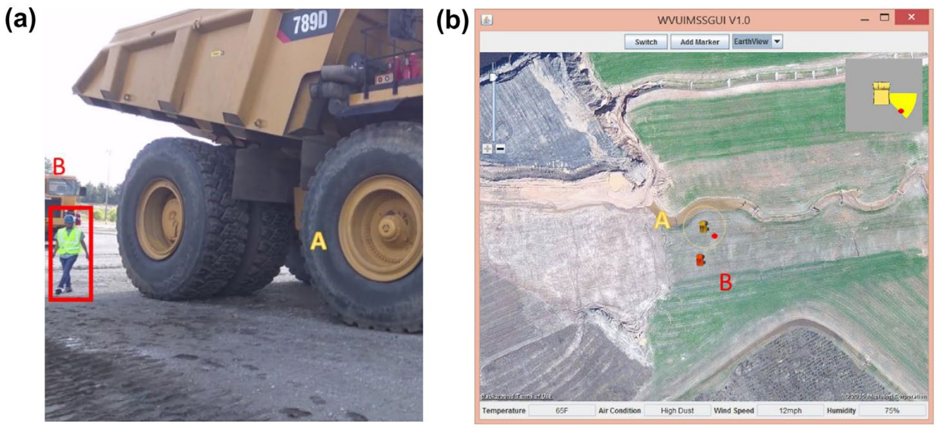


**Figure 9.** Testing of GUI with GPS and proximity sensor data. A and B in the GUI represent primary and secondary trucks, respectively. Note: Red dot represent position of the worker.

## 3. System implementation and testing

The prototype of the system was deployed and tested for accuracy in a surface coal mine in the southern United States. A photo taken in the mine with one of the mobile motes deployed on a CAT 769 haul truck is shown in Figure 6. The classification accuracy of the mobile motes systems in identifying different zones based on the RSSI values is shown in Figure 7. For distances of 3, 6 and 9 m from the truck, 90% of the time the zones were identified accurately. About 10% times, the zones were classified as the directly neighbouring zone.

The results of additional testing performed to test the ability of unified GUI to integrate and present information acquired from the GPS, ad hoc network and RF system are shown in Figures 8 and 9. Figure 8 shows the real-time position of an incoming truck B on the GUI with respect to the primary truck A. Please note that the primary truck is not visible in this figure. Result of this testing showed that the GUI was able to accurately show the position of the vehicles acquired using the GPS on the earth-view map developed using the map pre-processing method. Figure 9 shows real-time positions of truck B on the GUI and a moving worker with respect to the primary truck A. The position of the worker is shown using a red dot and using a proximity warning panel. Result of this testing showed that the GUI was able to simultaneously show the data acquired using the GPS and proximity sensors.

## 4. Discussion and conclusion

The system presented in this paper integrates and presents data acquired using GPS, ad hoc network and RF-based sensors using a unified GUI. The GUI implements an earth-view map, which is quite similar to that of a commercial GPS. The real-time positions of the user's vehicle with respect to other vehicles (acquired using ad hoc network) and objects (acquired using RF-based system) are presented on this map. One of the unique features of the proposed system is its ability to render the most recent earth-view map with accurate geographical data. Such a mapping feature allows the users to easily relate their position within the GUI with actual position in the mine, further enhancing users' awareness of surroundings. This is especially true when the same map/GUI also displays the positions of surrounding vehicles, obstacles and other objects.

Two-dimensional (2D) earth-view maps were used in the current study. Other feasible options are 2D plain map or three-dimensional (3D) earth-view maps. 2D plain maps lack the inherent GPS position-based surrounding awareness of 2D earth-view maps. 3D earth-view maps may provide enhanced surrounding awareness, but studies have shown that 3D maps were not superior to 2D maps for navigation tasks [17,18]. In terms of understanding the natural terrain, the 3D perspective is superior to a 2D view [19]. However, 2D maps allow for broader viewpoints without distortion and ambiguity. One can also argue that 3D earth view and perhaps 2D earth view may influence the cognitive load on the driver while using such systems during driving tasks. But the current literature on such comparisons is sparse. Future studies should evaluate the influence of different map views on cognitive load as well as on performance during driving.

The map customisation using masking/editing tool is another unique feature of the navigation system. This tool can be very efficient in generating custom warnings based on changed environmental, geographical conditions or hazards. New geographical upgrades that are not reflected in the maps can also be easily added to the navigation system with minimal efforts. This masking tool can also generate new routes on the map in case of severe weather conditions that lead to low visibility. The ad hoc wireless communication used in our system requires individual trucks to be in communication range of a central processing/dispatch unit. During a regular working day such map upgrades can be achieved by locating a dispatcher workstation at a common stay point, such as parking place, where vehicles visit frequently or during scheduled breaks, such as shift changeovers or lunch breaks. Additionally, repeaters that receive signals and retransmit at a higher level or higher power can be installed at such common stay points. Alternatively, a more expensive cellular or long-range multihop network could also be used to transmit the information required to generate dynamic map layering to vehicles.

Several sensor technologies have been implemented and/or proposed for proximity warnings. These technologies include radio detection and ranging (RADAR), light detection and ranging (LIDAR), cameras, GPS, tags-based RFID, or a combination of these technologies. Each technology has its pros and cons. The GPS and RFID-based technology used in the current study provides accurate and effective warnings. However, the GPS-based proximity system may be affected by satellite visibility; the RFID-based systems require management to ensure 100% compliance in terms of tags, as they do not identify untagged objects. Additional redundancy could be provided by incorporating a camera-based system. However, harsh environmental conditions in surface mines (poor lighting, fog, dust and dirt on the lenses) may affect image quality and the information generated by the cameras.

The prototype of the navigation system presented in this paper was deployed in a surface coal mine in the southern United States. The initial testing proved that the system was feasible in acquiring positions of the vehicles and other tagged objects. The unified GUI was found to be effective in displaying vehicle position on an earth-view mine map and providing zone-based proximity warnings. Future work will focus on conducting additional testing to evaluate user feedback and improving the navigation system by adding GUI-based interactive systems to generate dynamic layers. One possible addition to the dynamic layering feature is the use of a timestamp along with an edit so that one can observe how old a particular update is. Temporary updates such as 'slippery conditions' could also be automatically erased after a certain amount of time.

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