Application of Radio-Frequency Identification Systems to Collision Avoidance in Metal/Nonmetal Mines

Todd M. Ruff and Drew Hession-Kunz

***Abstract*—Collisions between haulage equipment and pedestrian workers or other vehicles claim an average of five lives each year in surface and underground metal/nonmetal mining operations. Many more workers are severely injured. Although technologies exist that could prevent these collisions, (radar, closed-circuit TV, and backup alarms), they do have limitations and are not being used widely. New developments in radio-frequency identification (RFID) systems show promise for reducing the number of collisions. This paper, originally presented in 1998, describes tests conducted on off-the-shelf RFID systems and the subsequent development of a custom RFID system that could be used for both surface and underground mining equipment.**

***Index Terms*—Collision warning system, powered haulage, radio-frequency identification.**

I. Introduction

RESEARCHERS at the Spokane Research Laboratory (SRL), National Institute for Occupational Safety and Health (NIOSH), Spokane, WA, have been studying methods to reduce accidents associated with collisions between mobile mining equipment and pedestrian workers or smaller vehicles. Preliminary research has focused on evaluating current technology used in detecting pedestrians or vehicles in the blind spots of large haulage equipment operated in both surface and underground metal/nonmetal mines. The limitations of current methods prompted researchers to develop a more reliable and robust method of warning an equipment operator of an impending collision.

During the period from 1992 to 1996, 23 workers were killed in surface and underground metal/nonmetal mining operations when they were crushed by mobile mining equipment. The number of near misses and nonfatal injuries is much higher.[1]

Although circumstances vary, most fatalities could have been avoided if the equipment operator and/or pedestrian had sufficient warning of the impending collision.

Paper PID 00–23, presented at the 1998 Industry Applications Society Annual Meeting, St. Louis, MO, October 12–16, and approved for publication in the IEEE Transactions on Industry Applications by the Mining Industry Committee of the IEEE Industry Applications Society. Manuscript submitted for review October 15, 1998 and released for publication October 15, 2000.

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Publisher Item Identifier S 0093-9994(01)00898-2.

[1]*MSHA Mining Accident Database* [Online]. Available: http://www.msha.gov

II. Evaluation of Existing Technology

Several technologies are available that provide equipment operators with information on objects in blind spots. These include radar units, video cameras, ultrasonic and infrared sensors, and radio-frequency transponders. Many of these technologies were developed for the transportation and automotive industries and a few are available for mining equipment. The first step of the current work was to determine why the available technologies are not being widely used in the mining industry.

A. Radar

Several discriminating backup alarms are available that are based on radar technology. Two of the more popular units were evaluated both in the laboratory and at field sites. The first unit, originally designed for school bus safety, was not robust enough for mining environments. The second unit was specifically designed for construction equipment and proved to be robust enough for surface mining applications. However, tests on surface haulage trucks revealed severe limitations because of numerous false alarms. For example, if the sensitivity was set high enough to detect a person at 20–30 ft from the vehicle, it would also detect buildings as far away as 100 ft. These findings are similar to those discussed in [1]. Recent developments in vehicular radar technology are discussed in [2].

B. Video

Video cameras that allow a vehicle operator to observe the area in the vehicle's blind spots have been used in several industries. Cameras have also been used in surface mining, but concerns remain regarding high maintenance requirements and durability. In underground mines, the same problems are compounded by low-light conditions. Another problem with cameras is that a collision can still occur if the operator forgets or is unable to check the video monitor. Despite these drawbacks, cameras can still be effective, especially if used in combination with a collision warning system.

C. Ultrasonic and Infrared

Backup alarms based on ultrasonic and infrared systems have been used in the automotive market with some success. No systems were found that were packaged to endure the environmental conditions and maintenance requirements of mining. Ultrasonic-based systems are difficult to package in a way that makes the system robust enough to handle the vibration of mining equipment and the harsh environment of

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a typical mine. Slow response times also limit their range [1]. Infrared systems are susceptible to generating false alarms caused by direct sunlight, reflections, and hot equipment [1].

D. Radio Frequency Identification (RFID)

The most promising technology seen to date involves the use of radio-frequency transmitting tags that are detected by a tag reader on the equipment. This technology is known as RFID and is used in many industries for asset tracking and security applications. Personnel and smaller vehicles are each outfitted with a tag that has a unique identification (ID) code. Each piece of large equipment has a tag detector or reader that "listens" for the unique transmitted frequency and ID of a tag in the equipment's blind spots. If any tag is detected, an alarm alerts the equipment operator.

Only one RFID collision warning system, manufactured by a foreign company, was available at the time of this report. The cost of this existing system was much higher than the cost of other collision warning sensors, but the potential of the technology justifies continued work to make this type of system more affordable for any size of mining operation. It is the goal of NIOSH researchers to develop a low-cost system that is applicable to both underground and surface mining operations.

RFID systems solve many of the problems of the earlier technologies. With a properly designed system, there is minimal chance of a false alarm. Either a tag is present in the read range of the tag reader or it is not. If every pedestrian worker is wearing a tag, an equipment operator will know if someone is in the blind spot of the equipment. Packaging of the reader and tags can be robust with no decrease in performance. An RFID system would involve very little maintenance and, finally, with new developments in radio-frequency components, costs and size requirements can easily be met.

III. Evaluating Off-the-Shelf RFID Systems

Researchers needed to determine if RFID was in fact suitable for use on mining equipment and whether costs could be kept low. The first step was to evaluate existing off-the-shelf systems for other applications, such as vehicle and asset tracking and security. The following specifications for system performance were set by NIOSH researchers and were based on typical distances of blind spots behind and to the sides of equipment, equipment characteristics, and cost requirements. The approach was to determine if an off-the-shelf system could be modified to meet the specifications and if not, to develop a custom system either in-house or under contract.

A. System Specifications

1) Tags: Tags must be small and unobtrusive. The tag could be worn on a belt or eventually mounted on a cap lamp battery for underground operations. The tag could be passive if the required read range of 50 ft is achieved. Otherwise, the tag should be powered by rechargeable batteries that last for at least 12 h. The cost of each tag would depend on the other uses of the tag system, e.g., personnel tracking, but should be under $40 per unit when produced in large quantities. The tags must be able to remain operational when exposed to shocks, vibration, and the wet, dirty mining environment. Supplying an audible alarm at the tag may be an option if power requirements and delays can be kept to a minimum. The following should apply to the tag:

dimensions	ss small as possible, but no larger than 3-in square × 1-in thick;
temperature	from −20 °C to 70 °C;
humidity	100%, rain, snow;
range	50-ft maximum;
delay	0.5-s maximum;
voltage	supplied by battery or 4-V dc if attached to cap lamp;
current	low enough for 12 h of operation;
transmit power	must meet limits of human exposure as per 47 CFR 2.1093;
cost	under $40 per unit.

2) Reader System: The functions of the reader system can be simplified to detect only the presence of a tag. It is not required that a unique ID of the tag be read, although this might be useful in other applications. The maximum working range of the system would need to be around 50 ft to allow the equipment operator time to stop if a tag suddenly entered the path of the machine. Each piece of mobile equipment would have one or more readers mounted on it. The number of readers would depend on their ability to sense a tag from any blind spot around the machine. The reader must have some method of ignoring the tag of the equipment operator while he is operating the machine. The system would have to be robust and able to handle jarring, vibration, and equipment wash-downs. The frequency of the system should not interfere with other radio systems or radio-remote-controlled equipment. The following should apply to the reader system:

dimensions	as small as possible but no larger than 1-ft square × 6-in thick;
temperature	from 20 °C to 70 °C;
humidity	100%, rain, snow;
range	50-ft maximum;
delay	0.5-s maximum;
voltage	12- or 24-V dc, depending on equipment;
transmit power	must be kept very low to avoid inducing current in blasting cap wires and also to meet the limits of human exposure as per 47 CFR 2.1091;
cost	under $1200 per unit, including the operator warning system.

3) Operator Warning System: Output from the reader would need to supply the operator with an indication that a tag is within the sensing range. Both audible and visual alarms are preferable. These devices must be robust, industrial-type indicators that are mounted in the operator's cab. The following should apply to the operator warning system:

physical	small indicator lamp and buzzer to indicate the presence of a tag; buzzer noise must be heard above equipment noise;
temperature	from −20 ∘C to 70 ∘C;
humidity	100%, rain, snow;
power	depends on output of reader;
cost	included in reader system.

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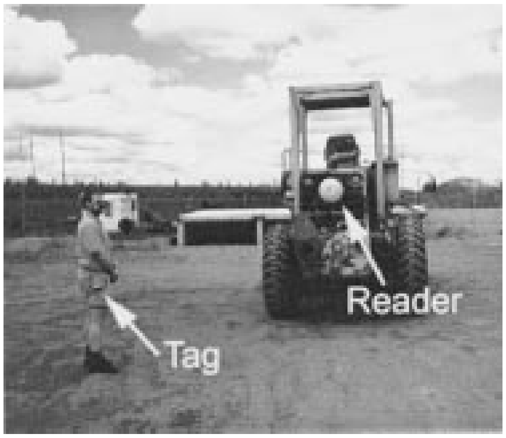

Fig. 1. Test configuration of UHF RFID system.

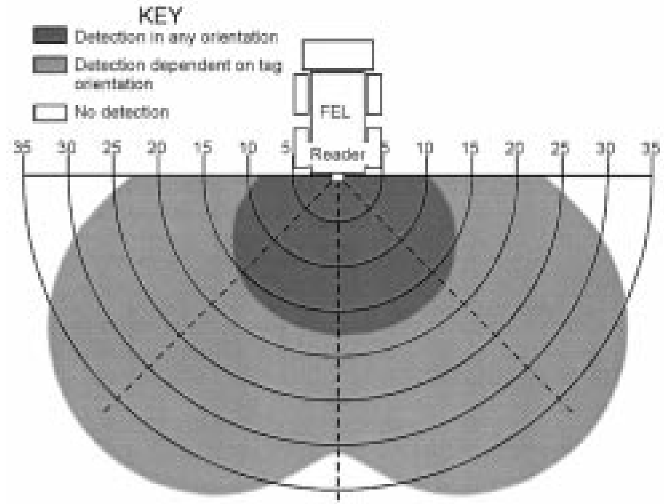

Fig. 2. Test results of UHF RFID system.

B. Evaluation of Off-the-Shelf Systems

Two RFID systems were purchased for evaluation.

System 1: The first system had been successfully applied to vehicle and asset tracking in other industries. It used active tags and a sophisticated reader that incorporated many functions that were not needed for the collision avoidance application. The system transmitted in the UHF spectrum and had a read range of over 200 ft. Modifications to the system allowed the read range to be decreased and incorporated an audible alarm if a tag was within range.

The system was tested on a 2-1/2-yd front-end loader at the SRL's Hanson site. Fig. 1 shows the configuration of the tests. The reader was mounted on the rear grill of the machine, and the tag was worn on the belt of the pedestrian. Several problems were encountered. Because of the sophistication of the reader's functions, a delay of at least 6 s was required between read times. This, of course, is unacceptable with mobile equipment moving at any speed. Researchers continued with tests, however, to define what type of detection zone could be achieved with the system.

As seen in Fig. 2, two detection zones were defined. The first zone (in dark gray) shows the area in which the reader detected the tag and alarmed nearly 100% of the time. Tag detection was not dependent on tag orientation. The second zone (in light gray) shows the area in which tag detection was sporadic. Tags within this zone were not detected when the pedestrian's body was directly between the tag and reader. The detection zones were adjustable out to 70 ft; however, because of the sporadic detection region, only a small reliable zone of around 20-ft radius from the front-end loader was useful. If the reliable detection zone was extended beyond 20 ft, false alarms from tags at distances of 100 ft from the front-end loader were prevalent.

The cost of this system was also a limiting factor. At $5000 for the reader and $100 for each tag, the cost would not be acceptable for widespread use. The manufacturer was contacted to see if it was interested in making modifications to the system to meet our specifications. It declined.

System 2: The second system tested was primarily used in security applications. Both the tags and the reader transmitted in the LF range. The tags were passive and were detected by the reader using a loop-type antenna mounted on the rear of the front-end loader. Fig. 3 shows the configuration of the tests. This system met cost requirements, but the detection range was only about 7 ft, too small to be used with mining equipment. While

Fig. 3. Test configuration of LF RFID system.

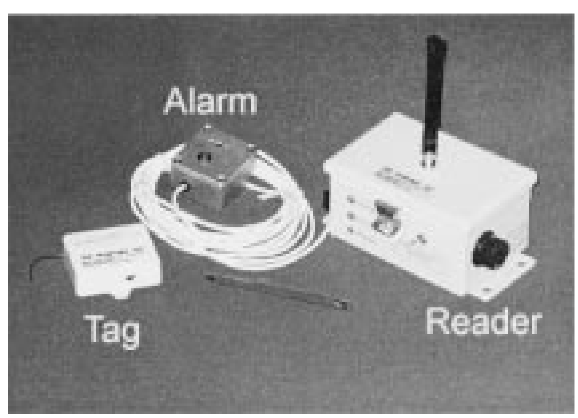

Fig. 4. IDI prototype collision avoidance system.

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body shielding was not a problem at these frequencies, the directionality of the tags was too severe for reliable operation. Extensive modifications to the antennae and packaging of the system would be required.

C. Conclusions

We determined that, rather than try to modify an existing system extensively, it would be more cost effective to develop our own system to meet the specifications. Preliminary efforts to develop a system in-house revealed the need for increased expertise and decreased development time. Development of the system is being done under contract with ID International Holdings (IDI), Concord, MA.

IV. System Development

A. Approach

Development of a customized collision warning system focused on using commercially available off-the-shelf low-cost radio-frequency components. While the specifications for the system were relaxed somewhat for the prototype, these specifications will have to be met in a final product. Thus, an iterative approach is being taken in the development of the system to make sure that each phase is progressing toward the specifications. This is a work in progress and the following sections describe the prototype system in its first phase.

B. System Description

The system, developed by IDI, consists of tags mounted on pedestrian workers' helmets, a reader–antenna unit on the vehicle, and an alarm unit mounted in the operator's cab and connected to the reader via a cable (Fig. 4). Each pedestrian worker and each vehicle in a work area or job site are outfitted with their appropriate parts of the system. A pedestrian's tag detected within the range of the reader activates the alarm, which warns the operator of the vehicle.

The prototype tags are housed in high-impact sealed plastic cases approximately 2.4 in × 2.7 in × 1 in. Components include a microprocessor, a 315-MHz transmitter, and an on-board battery. Production tags are projected to be less than one-quarter that size, plus antennae. The tags in the prototype system are fixed to the side of a hard hat with hook and loop fasteners. In production, permanent mounts will be used that will allow the tag to be removed or replaced.

Reader components include receiver, signal conditioning electronics, and microprocessor. The readers are housed in 4 in × 4 in × 6 in NEMA-type enclosures, plus a partial-coil whip antenna. These sealed, grounded steel boxes are mounted with bolts and brackets to the host vehicle, powered by the vehicle's 12-V dc system, and connected to the alarm unit in the operator's cab. The sealed alarm unit is 2.25 in × 1.75 in × 1.25 in, and has a light and a 105-dB alarm.

For testing and development purposes, the readers have two external switch-controlled adjustments: range and sensitivity. There are three selectable distance ranges (near, middle, and far) and a continuously adjustable sensitivity setting, which controls the software's signal discernment characteristics.

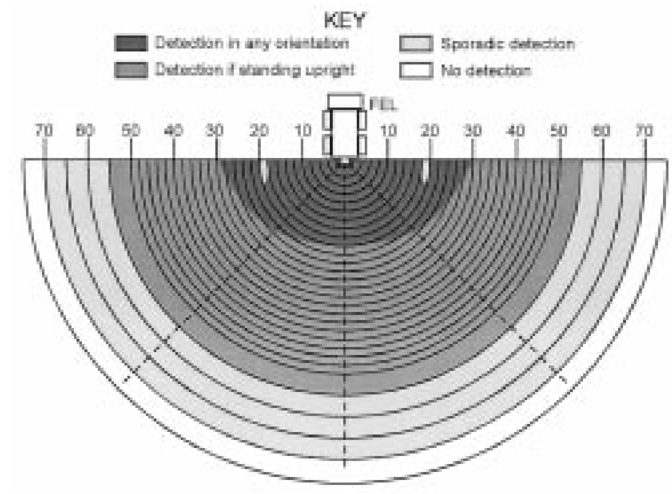

Fig. 5. Test results of IDI system.

Each tag transmits an "I'm here" signal three to four times per second. The reader receives the signal and converts it into a digital format. A noise rejection algorithm is applied to the signal by the software, and the signal is then checked for validity. If a valid signal is detected within the selected range, an alert condition is sent to the alarm unit, which flashes the light and buzzes the alarm, which is near the operator of the vehicle. If two tags are detected in the read range, a discernable "double buzz" alerts the driver to the presence of two or more tags. Up to four tags within the range of the reader can be discerned in this way.

Currently, the tags are powered by lithium coin cells, which have a projected working life of from six months to one year (verification tests to follow). Design features that contribute to extended battery life include a minimum parts count coupled with careful design of the transmission duty cycle. Developers are reviewing the addition of battery-checking capability or a "low-battery" alarm to ensure that the battery does not fail mid-shift, creating a hazardous condition.

C. Test Results

Tests were conducted on the prototype system using the same platform as previous tests on commercial systems. The reader was mounted on the rear of the front-end loader on the engine cover at a height of approximately 7 ft. Tags were placed on the side of the pedestrian's hard hat. Fig. 5 shows the various detection zones of the system at a medium range setting. The dark-gray area indicates the region in which a tag was detected nearly 100% of the time. Detection was not dependent on the physical orientation of the pedestrian. The medium-gray zone indicates the region in which tag detection was reliable if the pedestrian was standing upright so that the tag and its antenna were in line of sight of the reader. If the pedestrian bent over in this region, the reader failed to detect the tag. The light-gray zone indicates the region in which tag detection was unreliable and sporadic.

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D. Needed Improvements

Having completed the proof-of-concept phase, researchers will now focus on improvements to the effectiveness of the system. There are two important issues with the system as built. First is the potential for missing a tag as a result of changes in the physical orientation of the tag, i.e., if a worker bends over. Second is the potential for missing a tag because of nulls in the field within the range of the system. The directionality of the tags will be reduced through less directional antennae, both on the tags and the reader, or perhaps through orthogonal pairs of antennae, to improve uniformity of field strength in all directions. The nulls in the field will be addressed through analysis of the interaction of the tag's signal with the vehicle and changes in the mounting location and antennae of the readers.

Additionally, IDI is studying software modifications that would allow the system to discern between a signal in the excluded far field and one coming from a null within the expected range of the reader. This would also shorten the sporadic region of detection and minimize false alarms from tags that are a safe distance from the reader.

A further objective of the current phase is to test the radio frequency output of the tags to ensure that they fall within both the blasting cap safety limits and health exposure safety limits currently in force. These tests will determine if the tags can be safely worn during standard work shifts in all environments.

V. Conclusions

Avoiding collisions between pedestrian workers and vehicles in surface and underground mines is an important safety goal. While RFID systems hold promise for solving this problem, existing systems do not meet the functionality or cost needs of the industry. NIOSH is sponsoring the development of a low-cost high-reliability system through a contract with IDI. Once commercialized and properly deployed, this system could be important in reducing accidents and saving lives. For an update regarding this research, refer to [2].

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