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Image-Based Safety Assessment: Automated Spatial Safety Risk Identification of Earthmoving and Surface Mining Activities

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Abstract

This paper presents an automated image-based safety assessment method for earthmoving and surface mining activities. The literature review revealed the possible causes of accidents on earthmoving operations, investigated the spatial risk factors of these types of accident, and identified spatial data needs for automated safety assessment based on current safety regulations. Image-based data collection devices and algorithms for safety assessment were then evaluated. Analysis methods and rules for monitoring safety violations were also discussed. The experimental results showed that the safety assessment method collected spatial data using stereo vision cameras, applied object identification and tracking algorithms, and finally utilized identified and tracked object information for safety decision making.

Keywords: Automated safety assessment, Image-based object identification and tracking

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1. Introduction

The U.S. Occupational Safety and Health Administration (OSHA) states that employers are responsible for providing workers with a safe working environment (Wilson and Koehn, 2000). Earthmoving and surface mining activities generally involve high-risk operations because of several pieces of heavy machinery working simultaneously to load, haul, and dump construction materials. In fact, the U.S. Mine Safety and Health Administration (MSHA) in the United States reported that more than 30% of the total fatalities in coal and metal/nonmetal mining from 2004 to 2008 were caused by heavy machinery (MSHA, 2009a).

Given these statistics, many researchers have looked at positive ways to achieve a safer working environment by trying to identify risks and safety hazards on job sites. In general, job site safety has mostly been monitored and assessed based on manual inspections. Worksite supervisors, such as project managers, superintendents, safety managers or foremen investigate site hazards and report them to be either safe or unsafe using safety checklists. Besides on-site hazard inspections, all construction accidents are recorded and reported as well. According to safety regulations, all employers should keep records of workplace near-misses or injuries and report any work-related deaths or hospitalizations of employees (29 Code of Federal Regulations 1904 “Recording and Reporting Occupational Injuries and Illness) (OSHA, 2008). Using report forms, the incident type, the level of injury and damage, and the probable causes of the accident can be tracked.

Although such efforts have contributed to improving construction safety, they have relied highly on the observer’s competency in recognizing and measuring the acceptability or unacceptability of safety conditions (Ahmad and Gibb, 2004). In addition, such human observations are time-consuming, and it is almost impossible for observers to monitor site safety at all times; accidents are likely to arise suddenly. For these reasons, there is a need to automate safety assessment processes.

The primary purpose of the research presented in this paper is to develop an automated image-based safety assessment method for earthmoving and surface mining activities. The course of this research began with a literature review on the safety aspects of earthmoving and surface mining activities, including loading, hauling, and dumping operations (Section 2). The literature review revealed the possible causes of accidents for each activity, investigated the risk factors of these types of accident, and identified spatial data needs for safety assessment based on current safety regulations. Once the literature review was completed, the authors investigated data collection and interpretation methods. Image-based data collection devices and algorithms for safety assessment were evaluated (Section 3). Analysis methods and rules for monitoring safety violations were also discussed. The safety assessment method was then developed using informed and interpreted data for evaluating hazards on the working environment (Section 4). Field experiments assessed the feasibility of automated spatial data collection and safety assessment methods (Section 5).

2. Background Review

2.1 Accidents in earthmoving and surface mining activities

Earthmoving is engineering work that occurs through the moving of massive amounts of soil or unformed rock (Peurifoy and Schexnayder, 2002). Earthmoving is basically an operation in which material is removed from high spots and deposited in low spots for filling deficits or cutting excess material. The work of excavating, leveling, and piling up are considered to be earthmoving activities. Similarly, surface mining is an activity associated with mineral excavation and recovery carried out at the earth's surface (NIOSH, 2001). In general, loading, hauling, and dumping are fundamental operations for earthmoving and surface mining. In an earthmoving project, material is loaded from a cut area, hauled to a dumping area such as a fill area or a soil stockpile, and dumped. In surface mining, material is loaded from a quarry, hauled away, and dumped into a crusher. The crushed material is then loaded again onto haulage trucks for commercial delivery.

As the first step for identifying the data needs for safety assessment, accident categories of earthmoving and surface mining activities were investigated. According to the literature review (NIOSH, 1998; MSHA, 2001), the loading operation might cause "rolled over" (i.e., quarter rolls and other rolls on the same or a lower level), "collision" (i.e., collision with mobile equipment or other large stationary objects), "bounced or jarred" (i.e., a sudden release of energy that causes the machine to bounce or lurch forward or backward), "pinned between" (i.e., pinning between the bucket and frame of skid steer loaders or between the lift arms and frame), or "contacted power line" (i.e., contact with overhead power lines) accidents (MSHA, 1999; NIOSH, 2001). Next, the hauling operations may cause "fell over road edge" (i.e., traveling over a road edge and falling down to rest at a lower level), "hung up on road edge” (i.e., traveling onto a road edge and getting stuck without falling over), “rolled over,” “collision,” “bounced or jarred,” or “contacted power line” accidents. The dumping operations might cause “fell over the edge” (i.e., traveling through berms and falling over the edge), “hung up on edge,” “roll over,” “collision,” bounced or jarred,” or “contacted power line” accidents (Figure 1(a)).

<Insert Figure 1 here>

2.2 Risk factors of accidents

Following the investigation of accident causes, risk factors contributing to potential accidents were analyzed. Figure 1(b) shows an example of risk assessment diagrams (Clemen and Reilly, 2001) on loading, hauling, and dumping operations. Heavy-machinery-related accidents and their risk factors were reviewed from the Mine Safety and Health Administration’s and National Institute of Occupational Safety and Health’s fatality investigation reports and operation safety handbooks (NIOSH, 2001; NIOSH, 2007; MSHA, 1999; MSHA, 2001; MSHA, 2009b). For example, a fatality report about a stuck-by accident between a surface driller and a flatbed truck in 2009 indicated inadequate signs, limited visibility, high operation speed, workers’ carelessness, etc. as risk factors that resulted in the accident (MSHA, 2009b). Such risk factors identified were then categorized into three high-level risk factors: mechanical/hydraulic failures, operators’ errors, and poor operating conditions.

In general, mechanical or hydraulic failures such as defective brakes, carelessness of operators, excessive operation speeds, inadequate rules and signs, congested working areas, and poor ground surface conditions such as uneven ground and icy surface conditions can result in any kind of accident as shown in the risk factors depicted in Figure 1(b) (MSHA, 1999; NIOSH, 2001; MSHA, 2001; MSHA, 2009b). Poor site layout, curved roads, or large-scale heavy equipment machinery may create limited visibility, and accidents may happen at blind spots with limited visibility (Figure 1(b), A). Overloaded material can influence machine rollover, bouncing, or lurching (Figure 1(b), B). Power lines that are close enough to the ground can be hit by operating equipment (Figure 1(b), C). Operation-specifically, the undercutting of a material stockpile, that is, removing material from the base of the pile so that it compromises the stability of the pile, may result in instability of edge conditions in the loading and dumping operations. Such pile collapse can cause the rollover of machinery (Figure 1(b), D). Poor berm conditions or missing ones may cause "fell over edge," "hung up on edge," or "rolled over" accidents in hauling and dumping operations (Figure 1(b), E). A berm here has been defined as "a pile or mound of material intended to assist in preventing mobile equipment from traveling over the edge of a bank. Berms are normally used along the edge of haulage roads and dump sites" (NIOSH, 2001).

Among the risk factors examined, the safety assessment processes presented in this paper deal with risk factors associated with operator errors since the other two categories, poor operating conditions and mechanical/hydraulic failure, lean more toward design and maintenance perspectives. As shown in the diagrams, specific risk factors causing operator errors include excessive operation speeds, limited visibility to objects, access to unstable piles, ground, or edges, close access to berms, and traveling through berms or road edges. These risk factors can be categorized into three major risk factors: (1) excessive operation speeds, (2) dangerous access to the unsafe areas such as unstable piles, unstable ground, berms, road edges, etc., and (3) close proximity between objects such as heavy machinery and workers.

2.3 Best practices and spatial data needs for safety assessment

To identify spatial data needs supporting automated safety assessment by detecting the identified safety risk factors, safety regulations and best practices on selected risk factors were reviewed first. The Mine Safety and Health Administration enforces the Mine Act and Title 30 of the Code of Federal Regulation (30 CFR) (MSHA, 2008). The regulations showed that how they act for addressing risk factors. For instance, the safety regulation 77.1607(c), which is related to excessive operation speeds, requires that equipment operating speeds be consistent with conditions of roadways, grades, clearance, visibility, traffic, and the type of equipment used, and the operators should follow the speed limits selected to keep the equipment operating within the capabilities of their braking systems.

For each of the risk factors, best practices in terms of safety regulations were reviewed from the Mine Act and Title 30 of the Code of Federal Regulation (30 CFR) (MSHA, 2008), fatality investigation reports (NIOSH, 2007; MSHA, 2009b), and earthmoving operation handbooks (MSHA, 1999; MSHA, 2001; NIOSH, 2001) and data needs to support safety assessment were identified. Table 1 summarizes the mitigating risk factors, best practices, and data needs.

<Insert Table 1 here>

Table 1 showed that the fundamental spatial data needs supporting safety decision making include (1) moving speeds, (2) access (proximity) to dangerous areas, and (3) proximity to other objects and stopping distances. Such spatial data can be obtained using three-dimensional (3D) information about the job site components' and equipments' positions. The obtained data can be utilized as fundamental sources for safety assessment of earthmoving and surface mining activities, more specifically, loading, hauling, and dumping operations. Because of these data needs, the safety violations covered in this research are: speed limit violations, dangerous access violations, and close proximity violations.

3. Investigation of Image-Based Data Collection Devices and Algorithms for Spatial Safety Assessment

3.1 Analysis of data collection devices

The author reviewed image-based spatial data collection devices to find the most suitable one for this research. The evaluation criteria were established by considering the device's capability for object identification and 3D tracking on construction sites. Selected criteria included frame rate, outdoor application capability, reliable reading range, object localization capability, and 3D modeling capability. Four types of device were reviewed: LADARs, flash LADARs, single video cameras, and stereo vision cameras. Table 2 shows the specifications of the reviewed devices (Abeid et al., 2003; Teizer et al., 2005; Point Grey Research Inc., 2007; Leung et al., 2008; Chi et al., 2009).

< Insert Table 2 here >

Among the listed devices, the stereo vision camera best satisfied all of the criteria for device selection; it provides a fast frame rate, feasibility for outdoor applications, long reading range, and the capability for both object localization and 3D modeling. Because of this fit with the criteria, the authors decided to utilize stereo vision cameras for the research.

The "Bumblebee XB3," one of research-prototyped stereo vision cameras, was employed in this research (Figure 2(a)). "Bumblebee XB3" is a three-sensor multi-baseline (12cm and 24cm) stereo vision camera designed for improved flexibility and accuracy (Point Grey Research, Inc., 2007). It offers both 3D spatial information and 1280x960 maximum resolution within a 70° horizontal field of view. Its reliable maximum reading range is 75m with a measurement error rate of ±1m at 35m. The frame rate is 15 FPS, which is an acceptable one for real-time applications.

The "Bumblebee XB3" measures distances from the camera using the triangulation principle. First, the camera records two images simultaneously from the laterally-displaced lenses (Figure 2(b)). Then, for each pixel in the left image, a corresponding pixel in the right image is sought. To find such corresponding pixels (ex. P_1 and P_2), the Sum of Absolute Differences (SAD) correlation method is used (Point Grey Research, Inc., 2003). This method selects a neighborhood of a given square size from the reference image, and then compares this neighborhood to a number of neighborhoods in the other image in order to find the best match having the maximum likelihood of a correct response. After a correspondence between two images is established, the geometrical relationship (ex. A_1 and A_2) of the triangle is determined using the geometry of the camera and the displacement between the images. Using triangle parameters, the height of the triangle can be calculated, and this height represents the distance to the target.

<Insert Figure 2 here>

3.2 Analysis of image-based object identification and tracking algorithms

For transforming the acquired raw data into the data needed for safety assessment (moving speed and stopping distance, access to dangerous areas, and proximity to other objects), 3D object tracking and identification algorithms were investigated. “3D object tracking” is necessary because an object’s proximity and moving speed can be estimated using 3D information of object positions. “Object identification” is also required since safety rules are generally applied differently to different object types. For example, if two haulage trucks are approaching each other, it might be a hazard situation. However, if a loader is approaching a dump truck for material loading, this situation might not be dangerous. In addition, different speed limits need to be applied to different vehicle types. An access authority for the dangerous area can also be assigned only to specific equipment types. For these various reasons, object identification and tracking algorithms were employed to obtain the data needed for safety assessment.

Using spatial data acquired by the stereo vision camera, object identification and tracking algorithms were analyzed, modified, and adapted for the purposes of this research. Much research has been conducted in the field of computer vision to develop robust object identification and tracking algorithms. The algorithms on existing studies (Collins et al., 2001; Stauffer and Grimson, 2000; Javed and Shah, 2002; Bose and Grimson, 2004; Hu et al., 2004; Lalonde et al., 2007) mainly follow three steps: (1) moving object detection, (2) object correspondence for tracking within an image sequence, and (3) object classification, all of which provide the functional requirements of the proposed object identification method. Figure 3 illustrates an overview of the process. From the video stream (an image sequence), the stationary background regions are first subtracted and the dynamic foreground regions of moving objects are extracted based on the foreground detection and segmentation algorithm. Incomplete foreground regions with holes and disconnections are then reconstructed by applying morphological image processing and the foreground pixels are grouped into one region using the connected component algorithm so that the individual target region can be extracted. The connected regions now represent moving objects, and their correspondences are found for tracking within an image sequence. The object information including object shape and appearance is then put into classifiers and finally objects in the image are identified using the classifiers. The detailed information about technical challenges of applying these algorithms in the construction domain can be found in another article by the authors (Chi and Caldas, 2011). The identified and tracked object information is now ready to be used to acquire meaningful data for safety assessment.

< Insert Figure 3 here >

4. Determination of Safety Rules for Automated Spatial Safety Assessment of Earthmoving and Surface Mining Activities

4.1 Determination of safety rules for spatial safety risk identification

Once the object identification and tracking acquired the identified data needs, safety rules using the collected data were determined for actual safety decision making. The literature review identified violation types to be monitored for safety assessment: (1) speed limit violations, (2) access violations to dangerous areas, and (3) close proximity violations between objects. This section will provide in-depth explanation on how determined safety rules are able to detect such violations of earthmoving and surface mining activities, more specifically, loading, hauling, and dumping operations.

As the first step for rule determination, interviews were conducted with eight industrial safety experts. Interviewees were selected from various construction domains including a general contractor, a sub-contractor (an excavating company), and a government agency (The Department of Transportation). Industrial experience of the interviewees varied from minimum six years to maximum 37 years (21 years on the average). Positions of the interviewees included a vice president, a project manager, a field superintendent, a safety director, and a construction manager.

The interview questionnaire was prepared to listen to expert's opinions on three different topics: a speed limit violation, an access to dangerous areas, and a close proximity between heavy machinery. The questionnaire first asked agreement on identified safety risk factors and the interview results showed that all interviewees agreed that identified three violations can result in accidents during earthmoving equipment operation. The authors then discussed with them about how to formalize safety rules to detect identified risks. The determined safety rules will be discussed in the following sections.

Safety rules to detect speed limit violations

The interviewees agreed that it is important to monitor the speeds of earthmoving equipment to assure they are within the speed limit. From the discussion, the safety rule for speed limit violation detection was designed as "a speed limit violation occurs when moving speed of the tracked object exceeds its speed limit." This straightforward rule keeps monitoring the movement of on-site workers and heavy equipment and monitors violations.

Safety rules to detect dangerous access violations

The interviewees agreed that it is important to monitor earthmoving equipment's access to dangerous areas to assure they are within safety working environment. The interviewees also designated the following dangerous areas to be accessed: areas near highwalls, trenches, pits and holes, cracked and unstable ground, unstable material piles, road edges, dumping edges, wet roads, narrow access choke point, temporary fixed objects and crowded areas with construction personnel. The safety rule for dangerous access violation detection was designed as “a dangerous access violation occurs when the tracked object enters predetermined prohibited areas.” Besides the dangerous areas, authors and interviewees agreed that a material stockpile in which an access is authorized only for a loader performing material scooping needs to be considered as a strategic area for more effective safety assessment.

The safety rule first marks the spatial boundary of dangerous or strategic areas on a site map (these areas were manually plotted in this research) and then monitors objects’ proximity to the designated areas. A loader’s access to material stockpiles is allowed for material scooping.

Safety rules to detect close proximity violations

The object identification and tracking algorithms estimate proximity. It continuously tracks the 3D positions of heavy equipment machinery and workers, and it estimates the distances between objects. Now, there is a question of how to utilize this proximity information for detecting close proximity between objects.

In order to design a safety rule for close proximity violation detection, industrial standards for automobile crash avoidance system were reviewed. Many automobile manufacturers have designed on-board monitoring systems to help predict collision accidents, making it possible to reduce collision damage or take preventive action to avoid a collision (Toyota Motor Europe, 2008; Bogenrieder et al., 2009; Mobileye Technologies Limited, 2009). As operation principles, the system first monitors vehicle speed and steering angle, and detects the position, distance, and speed of any obstacle in front of the vehicle. The system then estimates a collision state with the vehicle or pedestrian ahead, taking into account the time to collision and the time to stop, which can be calculated by considering the inter-vehicular distance, the relative traveling speed, the motion vectors, and the braking system's capability. If the system judges that a collision may occur, the system then gives a warning to the driver and automatically applies the brakes to reduce vehicle speed. For example, 2.7 seconds before the time of a potentially imminent crash the driver gets a warning, or if the calculated deceleration needed to stop the vehicle before a collision exceeds a certain level, the system warns a credible collision status.

The rules used in the academic studies by Riaz et al. (2006) and Oloufa et al. (2003) followed similar standards as the automobile industry's standards. They considered motion vectors and the stopping distance for close proximity detection. This safety rule was applied to the proposed research. In order to estimate the approaching status, the applied rule predicts the post distance after 0.2 seconds between vehicles using their motion vectors and then compares this distance with the current proximity. If this distance is smaller than the proximity, we can say both vehicles are approaching each other.

The safety rule also assigns a safety margin that should surround heavy equipment machinery and then monitors other objects' proximity as they approach this boundary. The size of any given safety margin can be determined by the stopping distance of the machinery, which is defined as the traveling distance from the instant the operator perceives a hazard and applies the brakes to the instant the machinery completely stops. This time period was calculated with the assumption that operators of average skill can fully stop the machinery within the stopping distance.

The stopping distance (D) can be calculated by considering three components D_1, D_2, and D_3 (MSHA, 1999). The first component of the stopping distance, D_1, is "the distance that the vehicle travels during the time it takes for the driver to recognize that a stop is necessary and push on the brake pedal (MSHA, 1999)." This component accounts for the driver's perception and reaction time, which will vary by individual and circumstance. The Mine Safety and Health Administration (MSHA) recommended one second as this reaction time for operators of average skill (MSHA, 1999).

The second component of the stopping distance, D_2, is "the distance traveled in the time necessary for actuation of the braking system after the pedal is depressed (MSHA, 1999)." This lag time will vary depending on the size of truck and the braking system. MSHA defined Brake System Response Time in seconds based on vehicle gross weight (Table 3) in the regulation "57.14101 Brakes" (MSHA, 1999).

< Insert Table 3 here >

The third component of the stopping distance, D_3, is "the distance that fully-applied brakes need to bring the vehicle to stop (MSHA, 1999)." Assuming that the brakes are working properly, this distance depends on the speed of the vehicle when the brakes are applied, and on the vehicle's deceleration rate, which depends on the amount of friction available either between the brake components or between the tires and the road surface material. MSHA defined typical values for the coefficient of friction between rubber tires and various road surfaces (Table 4) (MSHA, 1999).

< Insert Table 4 here >

Now, the question is how can the gross weight of the machinery be obtained? After the classification process, the safety rule is able to determine the gross weight of the classified object using a pre-determined database. For instance, if an object is classified as a backhoe loader (e.g. CAT 430E), the process finds its weight from the database and assigns it as 25,000lbs (CAT, 2008). Using this weight, the system response time can be calculated.

The interviewees agreed that it is important to monitor this stopping distance of earthmoving equipment to assure they have safe proximity with other earthmoving equipment. The discussion also emphasized that close proximity can be allowed in a loading area when a loader approaches a truck for material loading. Table 5 summarizes how the safety rules were formalized and how they can be used for safety assessment.

< Insert Table 5 here >

4.2 Safety risk identification using safety rules for loading, hauling, and dumping operations

Safety risk identification for loading operations

A loader and a truck are both involved in a typical loading operation. The loader scoops material from the stockpile of soil or unformed rock and loads it onto the haulage truck. Since loading areas are generally congested with heavy machinery, different safety rules should be applied to different activity types. For example, if two haulage trucks are closely approaching each other, it might be considered a hazard situation. However, if a loader approaches a dump truck for material loading, it might not be dangerous. Also, an access to the material stockpile can be authorized only for a loader performing scooping works. Because of these differing conditions, travel and working patterns of heavy machinery need to be investigated.

Figure 4(a) shows an example of a typical loading zone for surface mining. In Figure 4(a), an area near a highwall is regarded as a dangerous working area. The safety risk identification method continuously tracks the movement of heavy machinery and estimates their proximity to other machinery as well as to pre-determined dangerous areas to facilitate safe decision-making. An area for an actual loading operation can be assigned by manually plotting 3D positions of the area. In this area, close proximity between a loader and a truck is allowed when the loader approaches the truck for material loading.

< Insert Figure 4 here >

Safety risk identification for hauling operations

The safety risk identification method first tracks the machine's moving speed, which is one of the most common risk factors in haulage-related accidents. As shown in Figure 4(b), the method first determines dangerous access areas near road edges, tracks proximity to these areas, and prevents the truck from traveling through the areas. In addition, the method sets a strategic spot near a road corner, a hill, or an intersection and calculates the proximity to the spot in order to help an operator have a clear sight distance. The method also estimates the proximity to other trucks and compares it with the calculated stopping distance for safe decision-making. Again, the stopping distance increases when the machinery moves faster and when the gross weight of heavy machinery increases, which results in more system response time for stopping.

Safety risk identification for dumping operations

The most common fatal dump-point accidents involve trucks going over the edge of a pile. Thus, the safety risk identification method primarily focuses on the estimation of proximity to the berm near the pile edge (Figure 4(c)). While the dump truck is backing up to the edge, the method estimates its proximity to the berm in order to prevent the truck from contacting the berm and potentially falling over it. The berm area can be manually assigned as dangerous areas by plotting 3D positions of the area. The method also monitors proximity to other trucks to avoid collision between machinery. If an unstable ground or edge exists in the dumping area, the area can be marked as an access prohibited area and the proximity to this area can also be monitored.

5. Testing Results

5.1 Object identification and tracking

The preliminary experiments were conducted for testing the object identification and tracking method. The actual hauling operations were monitored from the M. E. Ruby, Jr., limestone quarry located in Cedar Park, Texas, where 1.5 million tons of materials are produced every year. Four kinds of objects were involved in hauling operations; a wheel loader, a dump truck, a tractor truck, and a car. The training data was constructed using spatial characteristics of these objects from multiple poses. A total of 600 images (150 for each individual object) were trained to build a final data set. The algorithm codes were written using the C++ programming language in Microsoft Visual C++ 6.0. Two programming libraries were used: FlyCapture Software Development Kit (SDK) 1.7 and Triclops SDK 3.2 developed by Point Grey Research. In addition, Intel Open Source Computer Vision Library (OpenCV) (Intel Corporation, 2000) was employed for image processing and visualizing the results. A laptop computer (2.26 GHz Intel Core 2 Duo CPU and 1.98 GB of RAM) was used for program implementation.

Object identification

For analyzing the performance of object identification, a background subtraction algorithm first extracted moving objects from an image sequence captured by the stereo vision camera, and the spatial characteristics of the moving objects were then entered into two classifiers: a normal Bayes classifier or a neural network. Using these entered variables, the classifier identified each object as a wheel loader, a dump truck, a tractor truck, or a car. From 1,211 images processed, the total 975 objects appeared on the scene and were classified. Table 6 shows the detailed identification results.

< Insert Table 6 here >

Among the total 975 classifications, the normal Bayes classifier correctly identified objects 827 times, which resulted in a rate of 84.82% of identification accuracy (15.18% identification error rate). However, the neural network correctly identified objects 948 times, which resulted in a rate of 97.23% of identification accuracy (2.77% identification error rate). The results showed that the normal Bayes classifier had limitations in differentiating small objects with similar colors and shapes appearing far away from the camera position. That was because the algorithm determined a class with the highest probability disregarding the fact that the selected class also had low probability; in other words, when many classes had low probabilities, the algorithm picked one with the highest probability although its absolute value was still low. However, the neural network identified a class more precisely with its 30 hidden units, which contributed to more potential network flexibility. The results showed an acceptable rate of accuracy for the algorithms.

Object tracking

In the following phase of data collection, the tracking algorithm tracked haulage vehicles in a limestone quarry. The algorithm extracted 3D x, y, and z centroids of moving objects from the local field of view of the camera and transformed these local values into the global reference frame to plot some objects' positions on the global map. The original camera position and the rotation matrix were considered for coordinate conversion. In this experiment, conversion equations shown in Eq. 1 were used.

when $x > 0$,

$$X = P + \sqrt{x^2 + z^2} \times \cos\left(\tan^{-1}\left(\frac{z}{x}\right) - \theta\right)$$

$$Z = Q + \sqrt{x^2 + z^2} \times \sin\left(\tan^{-1}\left(\frac{z}{x}\right) - \theta\right)$$

when $x < 0$,

$$X = P + \sqrt{x^2 + z^2} \times \cos\left(\frac{\pi}{2} - \theta + \tan^{-1}\left(\frac{x}{z}\right)\right)$$

$$Z = Q + \sqrt{x^2 + z^2} \times \sin\left(\frac{\pi}{2} - \theta + \tan^{-1}\left(\frac{x}{z}\right)\right) \qquad \text{(Eq. 1)}$$

here, x represents the local horizontal position and z represents the local vertical position (the distance from the camera). P and Q represent x and z positions of the camera. θ represents the rotation angle between the local reference frame and the global reference frame. X and Z represent converted global positions. Figure 5(a) shows an image sequence of actual vehicle movements within the field of view of the camera (the local reference frame) and Figure 5(b) shows plotted trajectory of the object on the global map (the global reference frame). In Figure 5(a) rectangle boxes show identification results.

< Insert Figure 5 here >

The total of 10 individually-moving or simultaneously-moving heavy machinery including three wheel loaders, two dump trucks, four tractor trucks, and one car were monitored and tracked. A total of 1,211 images were processed. In general, tracking performance got worse at longer distances than 75m from the camera position, which was determined as a reliable maximum reading range of "Bumblebee XB3" by Point Grey Research. Figure 6 shows tracking results within the 75m distance from the camera position. Figure 6(a) illustrates the tracked trajectory of a dump truck which traveled back to the quarry exit for material delivery. Figure 6(b) illustrates the trajectories of two tractor trucks entering into the quarry. Here, the trajectory of the second truck was disconnected because the movement of the first truck blocked the line-of-sight of the camera.

< Insert Figure 6 here >

5.2 Safety assessment method

As the last step, actual safety violations were monitored from the experimental environment. The speed limit was set as 15 miles per hour (6.7056 meters per second). Figure 7 shows an example of safety logs. Safety assessment process basically recorded the classified object type and the violation time on the safety logs. Speed limit violations were first monitored with the actual speed information. Access violations were also identified when an object entered prohibited access areas. Here, highwalls were pre-determined as dangerous access areas in the experimental environment. Next, proximity violations were monitored when the actual distance between objects was smaller than the sum of stopping distances. From 1,211 images processed, the total 975 objects appeared on the scene and were classified. 47 encounters occurred between vehicles.

< Insert Figure 7 here >

47 speed limit violations and four proximity violations were monitored within the 75m reliable reading range. However, at longer distances than the 75m, unreliable results (80 speed limit violations, 111 access violations and 4 proximity violations) were caused by inaccurate tracking results. When we just consider the results within the 75m, some of speed limit violations seemed to be mistakenly monitored due to instant large tracking errors. Such false tracking error increased object’s moving speed and as a result false proximity violation occurred with the larger stopping distance.

This information can be utilized for real-time safety risk identification related to loading, hauling, and dumping operations. A speed limit violation can be an indicator to control excessive operation speeds of heavy machinery, and a dangerous access violation can prevent equipment operators from approaching dangerous areas.

Last, a proximity violation can determine dangerous operating conditions in terms of proximity. In other words, the developed image-based safety assessment method keeps monitoring heavy machinery operation on sites, and the number of detected violations indicates the level of operational risks related to earthmoving activities.

The developed safety assessment method evaluated safety violations frame by frame (three image frames per second), which resulted in the high rate of violations. In other words, if speed limit violations continuously occurred for three seconds, the total of nine violations was monitored by the method. In order to prevent the violations to be ignored by workers as nuisance noise, the safety assessment method needs to consider different time tolerance for violation detection. For instance, when a safety violation is continuously monitored during a certain time interval (ex. three seconds) the method identifies this case as a violation, not by the frame-by-frame approach.

5.3 Limitations, improvement opportunities, and future research

There are still limitations, improvement opportunities, and future research challenges to be addressed. First, integration of GPS and Ultra-Wide Band tracking devices and the developed image-based safety assessment method is expected to result in better performance on object identification and tracking with more accurate 3D spatial information. The tracking devices would be able to validate better the performance of the developed safety assessment method with ground truth information. The image-based method would complement the limited number of attachable tracking devices by providing clear site and object information such as the size of heavy equipment and the boundary information of dangerous areas. This future research should also consider more complicated earthmoving scenarios with a larger number of heavy equipment involved for further validation of the safety assessment method.

Second, a proper camera allocation plan that places cameras at strategic positions should be considered depending on the camera coverage. Bumblebee camera's reliable maximum vertical range is 75m and its horizontal field-of-view is 70º (Point Grey Research, Inc., 2007). Thus, the maximum horizontal reading range can be about 100m. Cameras need to be approximately located on the site using these numbers for implementation. For instance, if the original horizontal width of the site is about 300m, at least three cameras need to be horizontal located to cover all the areas. It is also important to consider that the tracking accuracy is usually deteriorated more at longer distances from the camera position. Thus, the optimized camera location with a proper camera network plan would improve monitoring quality and analysis results.

6. Conclusions

This research determined the data needs for spatial safety assessment and explained as to what spatial data is required for safety assessment or how data is related to construction accidents. This research surveyed accident types related to earthmoving operations, identified accident risk factors, explored current safety regulations and best practices, and finally identified spatial data needs for safety assessment studies.

Second, this research investigated how to collect needed data and utilize collected data to promote more informed and efficient safety decision making. The analyzed algorithms were designed to systematically collect and interpret safety-related data. The object identification and tracking algorithms were suited to detect, classify, and track on-site moving resources. The identification algorithms were able to precisely classify heavy machinery for automated reasoning. The tracking algorithms estimated three-dimensional boundaries of heavy machinery and the location of the machinery. The applied safety rules enabled automated violation detection, which showed how collected data were able to be utilized for safety decision making. Nevertheless, there are still limitations, improvement opportunities, and future research challenges to be addressed: integration of tracking devices and the image-based safety assessment method, further experiments with more complicated earthmoving scenarios, and camera allocation and network planning.

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Table 1 Best practices and data needs (MSHA, 1999; MSHA, 2001)

No.	Risk Factor	Best practice	Data need
1	High operation speed	Operators should follow the speed limits selected to keep the equipment operating within the capabilities of their braking systems.	Moving speed
		On curves, the speed must be limited to allow adequate traction.	
2	Access to dangerous areas	Berms should give the driver a visual indication of the location of the roadway edge and the driver should operate the vehicle without contacting berms.	Proximity to a road edge
		Operators should keep a vehicle back from the edge of the slope by a distance equal to at least the width of the berm.	
		Operators should not attempt to dump over the edge of the pile.	Proximity to a dumping edge
		Operators should back up perpendicular to the berm, not at an angle to the dumping edge.	
		Operators should use the berm as a visual indicator only, do not use it or rely on it to stop the truck.	
		The hazard area shall be posted with a warning against entry and, when left unattended, a barrier shall be installed to impede unauthorized entry.	Proximity to dangerous areas (a hazard area, an area between machinery and highwall, and a unstable edge)
		Work or travel between machinery or equipment and the highwall or bank shall be prohibited.	
		Access to the unstable edge of the dumping area shall be restricted.	
3	Close proximity between objects	Where vehicles appear to be following one another too closely, the stopping distance can be used for guidance on the distance that should be maintained between vehicles.	Stopping distance, proximity to other vehicles
		Operators should check adequate clearance and visibility, especially to blind spots, before operation.	Proximity to other objects

Table 2 Comparison of data collection devices

Devices	Frame rate	Outdoor application	Reliable maximum reading range	Object localization	3D modeling
LADAR	Slow (<1Hz)	Yes	Very long (>100m)	Yes	Yes
Flash LADAR	Fast (>10Hz)	No	Short (<10m)	Yes	Yes
Video camera	Fast (>10Hz)	Yes	Long (>50m)	No	No
Stereo vision camera	Fast (>10Hz)	Yes	Long (>50m)	Yes	Yes

Table 3 Estimated brake system response time based on vehicle gross weight (MSHA, 1999)

Gross weight (lbs)	1 - 36k	36k - 70k	70k - 140k	140k - 250k	250k - 400k
System response time (sec)	0.5	1.0	1.5	2.0	2.25

Table 4 Coefficient of friction between rubber tires and various road surfaces (MSHA, 1999)

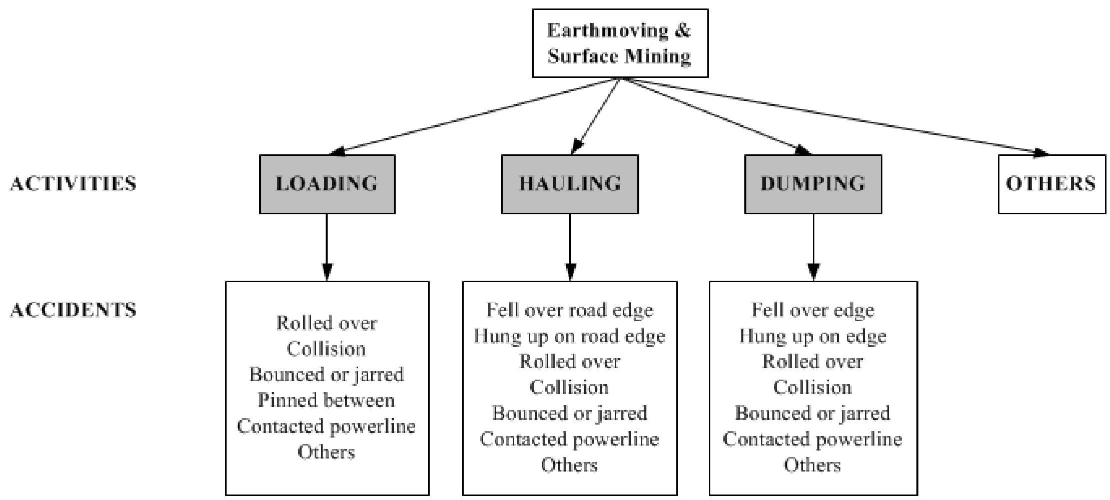
Material	Dry	Wet	Material	Dry	Wet
Concrete	0.90	0.60-0.80	Gravel road, firm	0.50-0.80	0.30-0.60
Clay	0.60-0.90	0.10-0.30	Gravel road, loose	0.20-0.40	0.30-0.50
Sand, loose	0.10-0.20	0.10-0.40	Snow, packed	0.10-0.40	0
Quarry pit	0.65	-	Ice	0	0

Table 5 Safety rules to detect safety violations

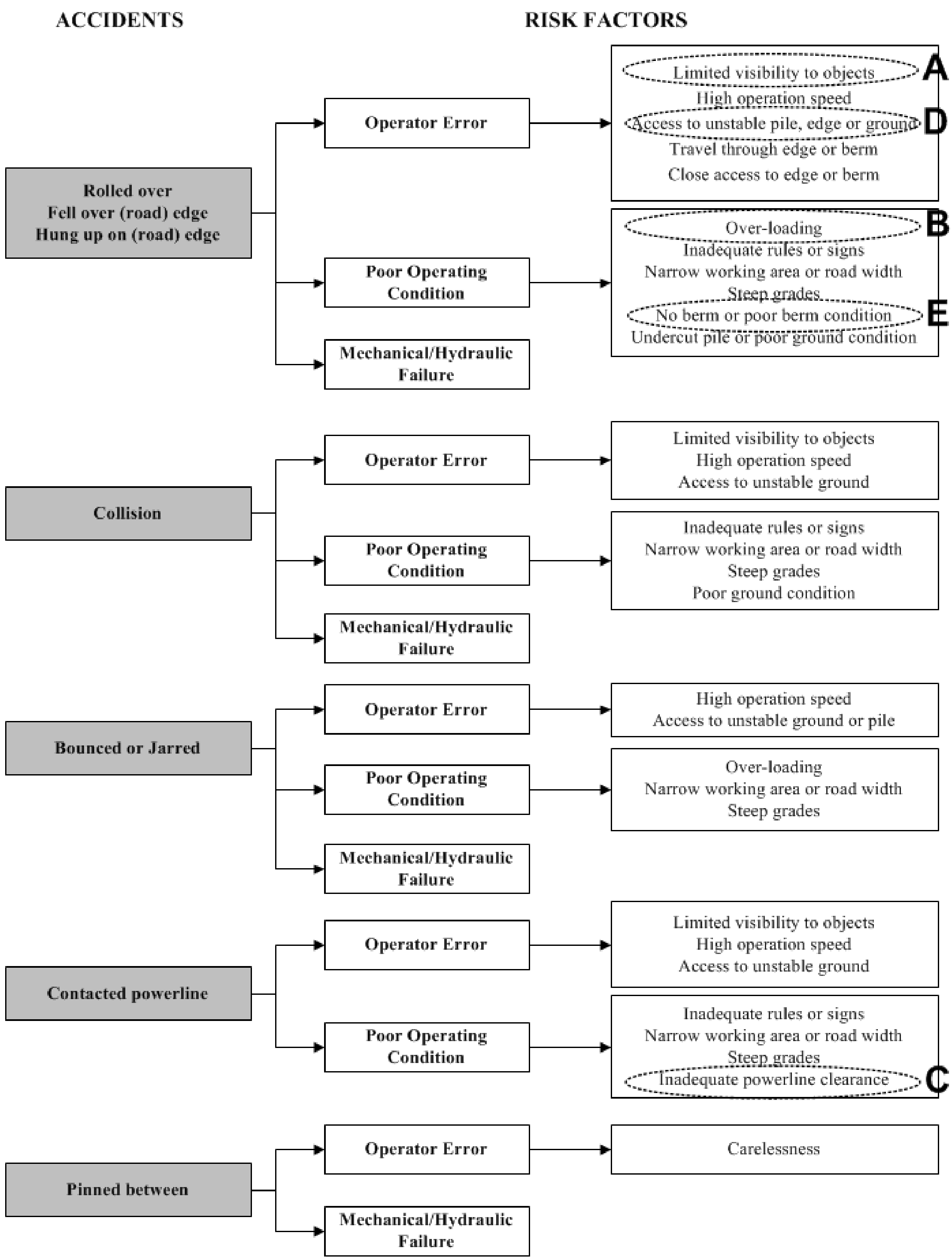
No.	Violation Type	Designed Safety Rule	Design Sources	Implementation Strategy
1	Speed limit violations	A speed limit violation occurs when moving speed of the tracked object exceeds its speed limit.	(1) Review on safety regulations, (2) Discussion with industrial experts	The rule keeps monitoring the movement of on-site workers and heavy equipment and monitors speed limit violations.
2	Dangerous access violations	A dangerous access violation occurs when the tracked object enters predetermined prohibited areas.	(1) Review on safety regulations, (2) Discussion with industrial experts	The rule first marks the spatial boundary of dangerous areas on a site map and then monitors objects' proximity to the designated areas. A loader's access to material stockpiles is allowed for material scooping.
3	Close proximity violations	A close proximity violation occurs when actual distance between tracked objects is smaller than the sum of their stopping distances.	(1) Review on industrial standards for automobile crash avoidance systems, (2) Review on academic safety studies, (3) Review on safety regulations, (4) Discussion with industrial experts	The rule assigns a safety margin that should surround heavy equipment machinery based on the stopping distance, and then monitors other objects' proximity as they approach this boundary. Close proximity is allowed when a loader approaches a truck for material loading.

Table 6 Object identification results

Trial	1	2	3	4	5	6	7	8	Total
Number of Object Classified	117	67	60	121	98	207	215	90	975
Normal Bayes Classifier									
Incorrect Identification	8	29	43	13	7	15	27	6	148
Identification Accuracy (%)	93.16	56.72	28.33	89.26	92.86	92.75	87.44	93.33	84.82
Neural Network									
Incorrect Identification	5	6	3	0	1	5	3	4	27
Identification Accuracy (%)	95.73	91.04	95.00	100	98.98	97.58	98.60	95.56	97.23



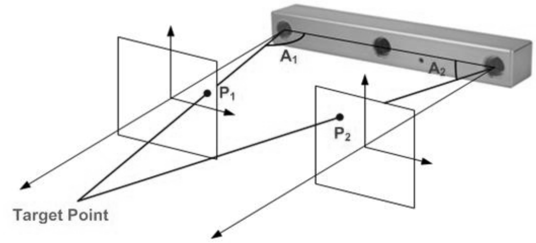
(a) Typical activities and accidents of earthmoving and surface mining



(b) Accidental risk factors

Figure 1 Risk assessment diagrams on loading, hauling, and dumping operations

(a)



(b)

Figure 2 Stereo vision camera: (a) “Bumblebee XB3”, (b) distance measuring principle (Barnard and Fisher, 1982; Point Grey Research, Inc., 2007)

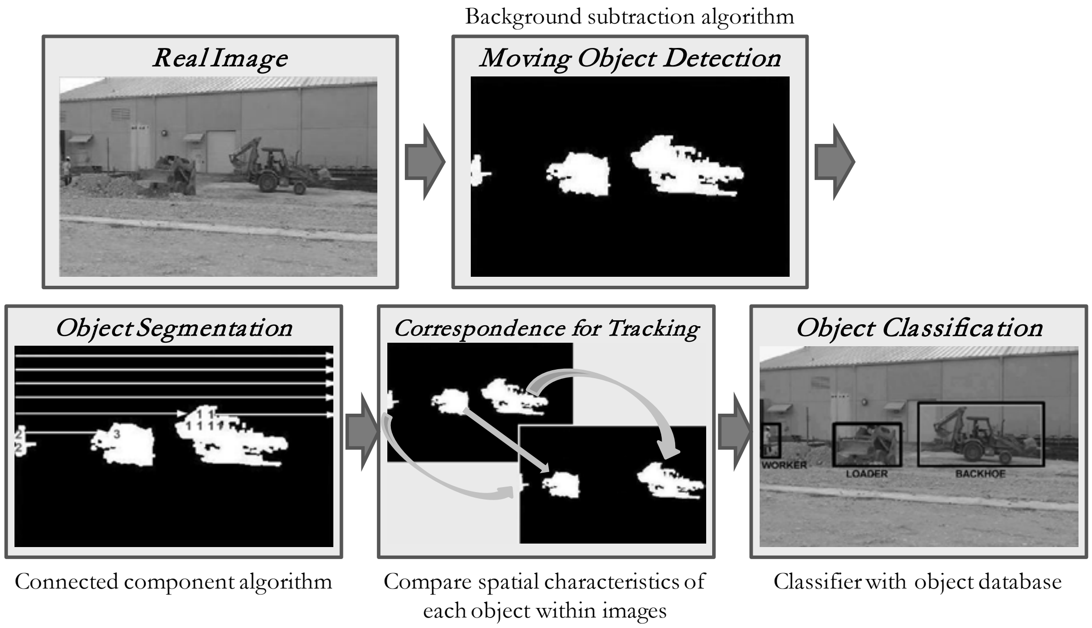
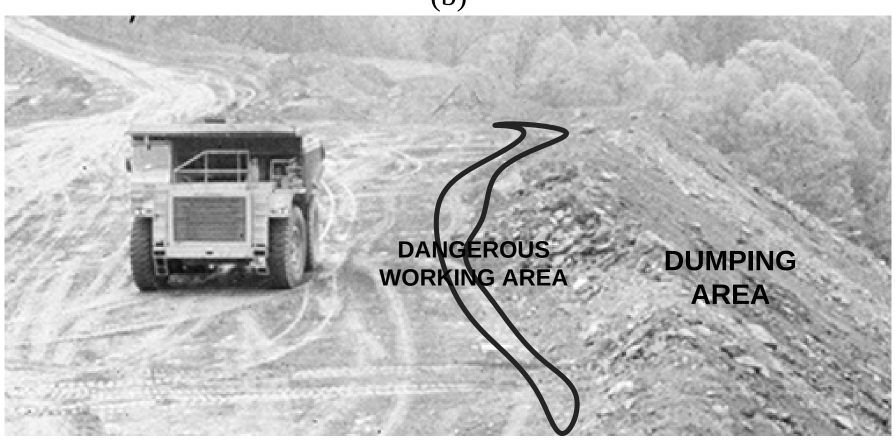


Figure 3 Overview of object identification and tracking process

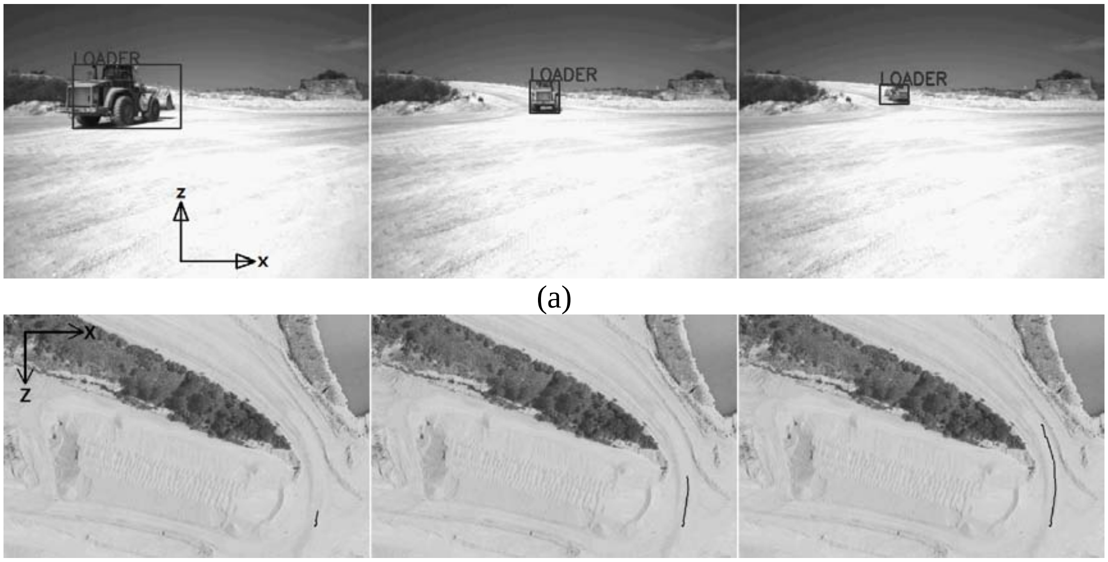
(a)

(b)



(c)

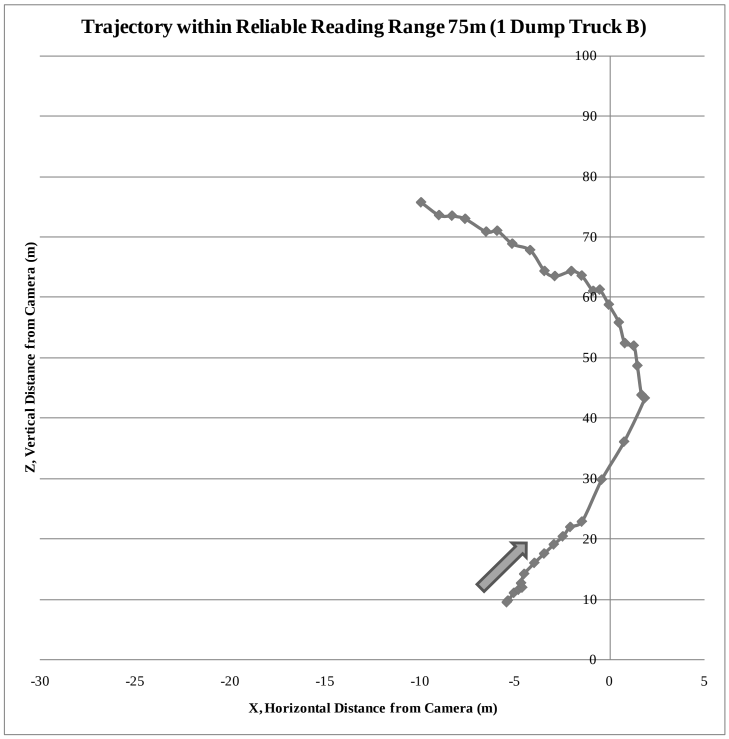
Figure 4 Safety assessment for earthmoving and surface mining activities: (a) loading operation, (b) hauling operation, (c) dumping operation



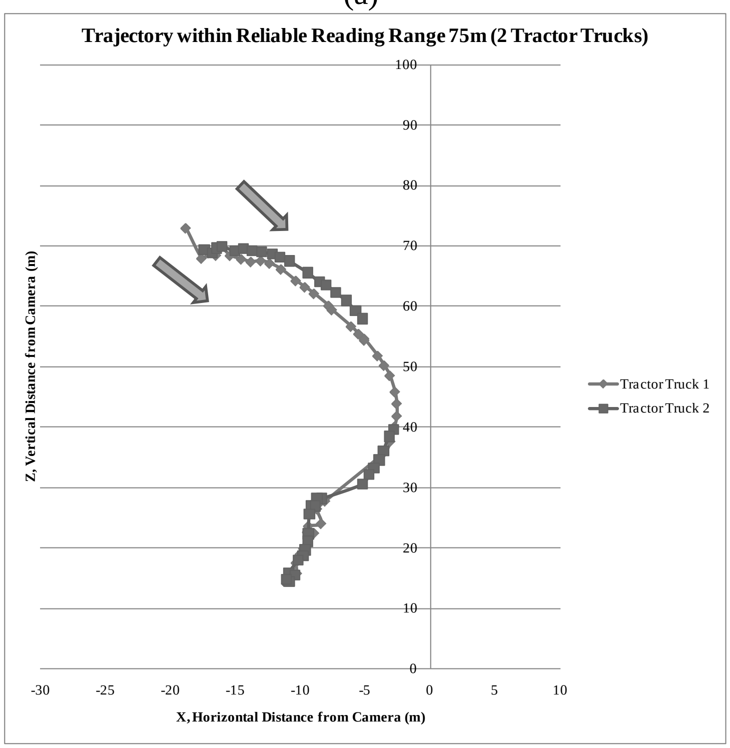
(a)

(b)

Figure 5 Object tracking result: (a) original movement of tracked loader, (b) trajectory of the loader (top view)

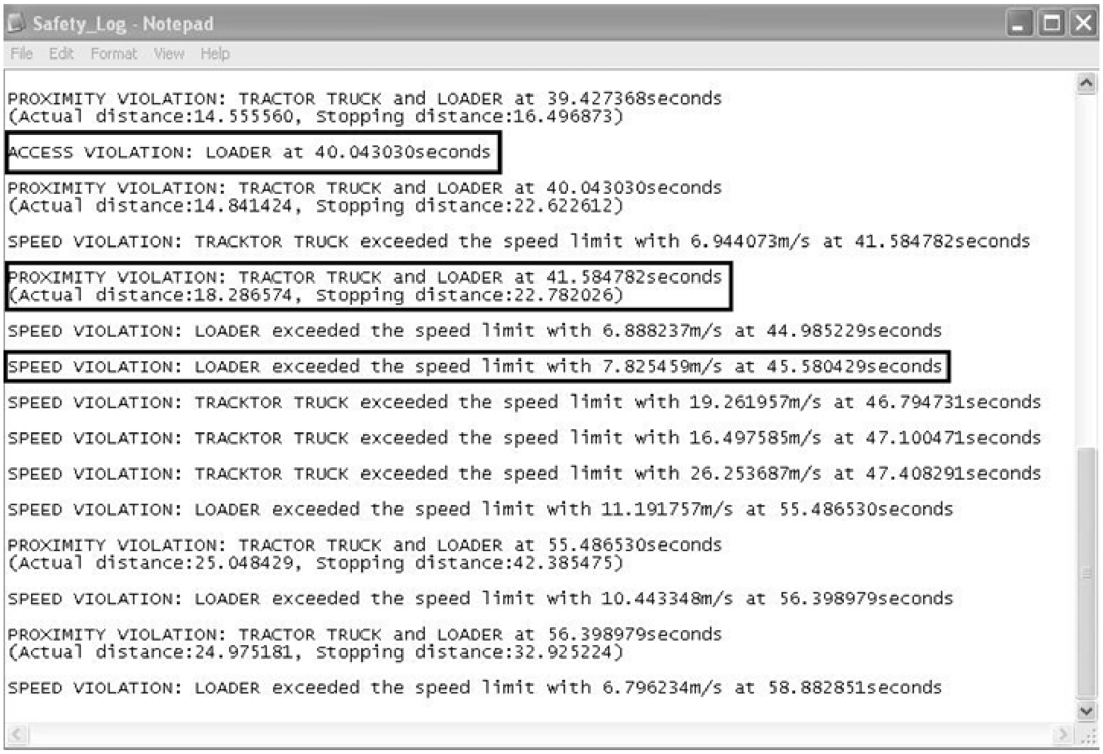


(a)



(b)

Figure 6 Trajectory of the tracked object (top view): (a) trajectory of a dump truck, (b) trajectory of two tractor trucks


Safety_Log - Notepad

File Edit Format View Help

PROXIMITY VIOLATION: TRACTOR TRUCK and LOADER at 39.427368seconds
(Actual distance:14.555560, Stopping distance:16.496873)

ACCESS VIOLATION: LOADER at 40.043030seconds

PROXIMITY VIOLATION: TRACTOR TRUCK and LOADER at 40.043030seconds
(Actual distance:14.841424, Stopping distance:22.622612)

SPEED VIOLATION: TRACKTOR TRUCK exceeded the speed limit with 6.944073m/s at 41.584782seconds

PROXIMITY VIOLATION: TRACTOR TRUCK and LOADER at 41.584782seconds
(Actual distance:18.286574, Stopping distance:22.782026)

SPEED VIOLATION: LOADER exceeded the speed limit with 6.888237m/s at 44.985229seconds

SPEED VIOLATION: LOADER exceeded the speed limit with 7.825459m/s at 45.580429seconds

SPEED VIOLATION: TRACKTOR TRUCK exceeded the speed limit with 19.261957m/s at 46.794731seconds

SPEED VIOLATION: TRACKTOR TRUCK exceeded the speed limit with 16.497585m/s at 47.100471seconds

SPEED VIOLATION: TRACKTOR TRUCK exceeded the speed limit with 26.253687m/s at 47.408291seconds

SPEED VIOLATION: LOADER exceeded the speed limit with 11.191757m/s at 55.486530seconds

PROXIMITY VIOLATION: TRACTOR TRUCK and LOADER at 55.486530seconds
(Actual distance:25.048429, Stopping distance:42.385475)

SPEED VIOLATION: LOADER exceeded the speed limit with 10.443348m/s at 56.398979seconds

PROXIMITY VIOLATION: TRACTOR TRUCK and LOADER at 56.398979seconds
(Actual distance:24.975181, Stopping distance:32.925224)

SPEED VIOLATION: LOADER exceeded the speed limit with 6.796234m/s at 58.882851seconds

Figure 7 Example of safety logs