Development of an Automated Safety Assessment Framework for Construction Activities

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Abstract

This paper presents an ongoing research project concerning the development of an automated safety assessment framework for earthmoving and surface mining activities. This research seeks to determine data needs for safety assessment and investigates how to utilize collected data to promote more informed and efficient safety decision-making. The research first examined accidents and fatalities involved with earthmoving and surface mining activities—more specifically, those involving loading, hauling, and dumping operations,—investigated risk factors involved with the accidents, and finally identified data needs for safety assessment based on safety regulations and practices. An automated safety assessment method was then developed using the data needs that had been identified. This research is expected to contribute to the introduction of a fundamental framework for automated safety assessment and the systematic collection of safety-related data from construction activities. Implementation of the entire safety assessment process on actual construction sites remains a task for future research.

Background and Motivation

A construction site is typically equipment-intensive, and more than a thousand workers die every year in the United States due to heavy-equipment-related fatalities. The Bureau of Labor Statistics (BLS) analyzed primary and secondary sources of machinery-related fatalities from 2003 to 2006 based on heavy equipment types (BLS 2003-2006). They reported that 1,644 (34%) of the total 4,796 fatalities resulted from operation of the six common types of heavy equipment machinery: excavating machinery, loaders, road grading and surfacing machinery, cranes, trucks, and forklifts. Given these fatality numbers, many researchers have looked at positive ways to achieve safer working environments, trying to identify risks and safety hazards on a site. Questions about how safe a site is or what kind of safety culture already exists depend upon how many risk factors exist in construction activities, and site safety assessment is a pre-requisite to identifying such risk factors that contribute to accident potential that need to be controlled (Ahmad and Gibb 2004). 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 time; accidents are likely to arise suddenly.

For these reasons, much research has been performed for automating the safety assessment process. Although these studies have made an effort toward safety improvement, most of them have merely presented site information acquisition and processing techniques without providing in-depth explanations as to what kinds of data are required for safety assessment or how data is related to construction accidents. For example, some studies asserted that the on-site tracking of objects is important for safety assessment, but they did not show which types of accidents were prevented by object tracking and how the object tracking was used for safety assessment. Thus, we have a research need for the development of a step-by-step safety assessment framework covering activity risk and data need analyses to safety decision-making.

The primary purpose of this research is to develop an automated safety assessment framework for construction activities. The course of this research began with a literature review on earthmoving and surface mining activities, specifically, loading, hauling, and dumping operations. The research examined possible accidents and fatalities involved with each activity, investigated risk factors of such accidents, and finally, identified data needs for safety assessment based on safety regulations and best practices. The automated safety assessment method was then developed using informed and interpreted data for understanding whether a working environment is safe or unsafe.

Accidents in Earthmoving and Surface Mining Activities

As a first step for safety assessment, accident categories of earthmoving and surface mining activities—specifically, loading, hauling, and dumping operations— were investigated. Accidents resulting from maintenance or ingress/egress were not considered; only accidents caused by equipment operation were examined.

According to the literature reviewed (NIOSH 1998, MSHA 2001), the loading operation might cause “rolled overs” (i.e., quarter rolls and other rolls on the same or lower level), “collisions” (i.e., collision with mobile equipment or other large stationary objects), “bounced or jarred” accidents (i.e., a sudden release of energy that caused the machine to bounce or lurch forward or backward), “pinned between” accidents (i.e., pinning between the bucket and frame of skid steer loaders or between the lift arms and frame), and “contacted power line” accidents (i.e., contact with overhead power lines). In addition, the Mine Safety and Heath Administration (MSHA 1999) and the National Institute for Occupational Safety and Health (NIOSH 2001) classified accidents related to hauling operations. The accidents mainly contained “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 overs,” “collisions,” bounced or jarred” and “contacted power line”. MSHA (2001) and NIOSH (2001) also investigated accidents at a dumping site. The common accident types included “fell over the edge” (i.e., traveling through berms and falling over the edge), “hung up on edge,” “roll overs,” “collisions,” bounced or jarred,” and “contacted power line.”

Risk Factors of Accidents

Following the investigation of accident causes, risk factors contributing to accident potential were analyzed. Figure 1 shows an example of risk assessment diagrams on the dumping operation.

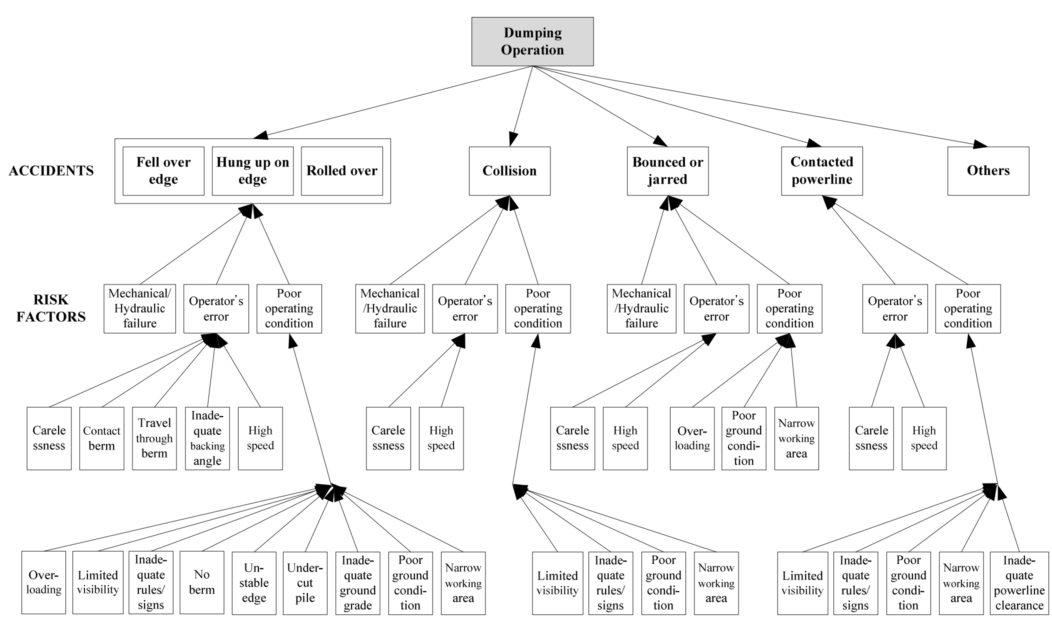

Figure 1 Risk assessment diagram on dumping operation

In general, mechanical or hydraulic failures such as defective brakes and rollover protective structure, careless attitudes of operators, an excessive rate of operation speed, inadequate rules and signs, a congested working area, and poor ground surface conditions such as uneven ground and icy surface conditions can result in any kind of accident (risk factors in Figure 1 - MSHA 1999, NIOSH 2001, MSHA 2001). Poor site layout, a curved road, or large-scale heavy equipment machinery may create limited visibility, and accidents might happen at blind spots with limited visibility. Overloaded material can influence machine rollover, bouncing, or lurching. Power lines that are close enough to the ground can be contacted by operating equipment. Operation-specifically, the undercutting of a material stockpile, that is, removing material from the base of a pile so that it compromises the stability of the pile, may result in instability of edge conditions in the loading and dumping operations, and pile collapse can cause rollover of machinery. A berm 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). Poor berm conditions or missing ones may cause "fell over edge," "hung up on edge," or "rolled over" accidents in hauling and dumping operations.

The safety assessment process proposed in this research deals with risk factors associated with operator errors among the risk factors examined, since the other two categories, poor operating conditions and mechanical/hydraulic failure, lean more toward design and maintenance perspectives. Specific risk factors causing operator errors include careless operation such as berm contact or inadequate backing angle, high operation speed, and traveling through an edge or a dangerous area.

Best Practices and Data Needs for Safety Assessment

The Mine Safety and Health Administration enforces the Mine Act and Title 30 of the Code of Federal Regulation (30 CFR) (MSHA 2008). For every risk factor, meeting best practices in terms of safety regulations were discussed, and finally, data needs to support safety assessment were identified. Table 1 explains best practices mitigating risk factors and identified data needs.

Data needs discussed in Table 1 can be classified into five categories: (1) moving speed of the equipment, (2) stopping distance of the equipment, (3) proximity to strategic spots, (4) proximity to dangerous areas, and (5) proximity to other on-site objects. The strategic spots include a road curve, a hill point, a road intersection, a road edge (berm), and a dumping edge (berm). The dangerous areas contain a specified hazard area, an area between machinery or equipment and the highwall or bank, and an unstable edge of the dumping area. These data can be used as fundamental sources for automated safety assessment of earthmoving and surface mining activities, specifically, loading, hauling, and dumping operations.

Before acquiring identified data, two pre-requisite steps need to be considered. First, "3D object tracking" is necessary because an object's proximity and moving speed can be estimated using three-dimensional information of object positions. Second, "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 should precede safety assessment.

Pre-requisite Steps: Object Identification and Tracking

In this research, a stereo vision camera was used for acquiring the raw data needed for identification and tracking. Such a camera provides a fast frame rate, feasibility for outdoor applications, long reading range, and the capability for both object localization and 3D modeling. Using this camera, object identification and tracking algorithms were analyzed, modified, and adapted for the proposed construction safety application. Much research has been conducted in the field of computer vision study to develop robust tracking and identification algorithms. The algorithms developed in previous studies (Collins et al. 2001, Stauffer and Grimson 2000, Javed and Shah 2002, Bose and Grimson 2004, Hu et al. 2004) mainly follow these three steps: (1) moving object detection, (2) object correspondence, and (3) object classification. The first step, "moving object detection," aims at separating the regions of motion corresponding to moving objects from the rest of an image (Hu et al. 2004). The second step, "object correspondence," aims at taking the segmented moving regions and matching them to find a corresponding region within an image sequence. The last step, "object classification," aims at classifying moving regions by using common shapes, appearances, or movements (Stauffer and Grimson 2000). Background subtraction algorithms, morphological image processing techniques, connected component algorithms, and different classifiers were reviewed, customized, and employed for this research. The detailed information can be found in another article by the authors (Chi and Caldas, 2008). The identified and tracked object information is now ready to be used to acquire meaningful data for safety assessment.

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

No.	Risk factor	Best practice	Data need
1	High 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	Traveling through an edge	When a vehicle is rounding a curve, cresting a hill, descending a grade, or approaching an intersection, a potentially hazardous condition may exist if the sight distance is less than the estimated stopping distance.	Sight distance (proximity to a curve, a hill, and an intersection), stopping distance
		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 a slope by a distance equal to at least the width of the berm.	
		Operators should not attempt to dump over the edge of a pile.	Proximity to a dumping edge
		Operators should back up perpendicular to a berm, not at an angle to the dumping edge.	
		Operators should use a berm as a visual indicator only, not rely on it to stop the truck.	
3	Traveling through a dangerous area	The hazard area should be marked with a warning against entry, and, when left unattended, a barrier should be installed to impede unauthorized entry.	Proximity to dangerous areas (a hazard area, an area between machinery and highwall, and an unstable edge)
		Work or travel between machinery or equipment and the highwall or bank should be prohibited.	
		Access to the unstable edge of the dumping area should be restricted.	
4	Careless operation	If vehicles appear to be following one another too closely, the stopping distance should be used for guidance on the distance that should be maintained between the vehicles.	Stopping distance, proximity to other vehicles
		Operators should check for adequate clearance and visibility, especially blind spots, before operation.	Proximity to other on-site objects

Safety Assessment for Earthmoving and Surface Mining Activities

Estimation of proximity to on-site objects

The proposed safety assessment method estimates proximity. It continuously tracks the 3D positions of heavy equipment machinery and workers, and it estimates the distances between objects. The process first 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 (CSG, Inc. 2008). 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 can be calculated using the following equation (MSHA 2008, CSG, Inc. 2008):

$$d = \frac{{v_0}^2}{2g\mu} + (t_s + t_0) \cdot v_0 \qquad (1)$$

here, v0 is the velocity of the heavy equipment, which can be estimated by considering the different positions of the object's volume centroids within an image sequence. g is gravitational acceleration (9.81 m/s2). μ is the friction coefficient between the tires and the road. The Mine Safety and Health Administration (MSHA) defined typical values for the coefficient of friction between rubber tires and various road surfaces (Table 2) (MSHA 1999). ts is system response time, and MSHA defined this time based on vehicle gross weight (Table 3) in the regulation "57.14101 Brakes" (MSHA 2008). Last, t0 is operator response time, and MSHA determined one second to be the operator response time for those of average skill (MSHA 2008).

Table 2 Coefficient of friction between rubber tires and various road surfaces

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 3 Estimated system response time based on vehicle gross weight

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

After the classification process, the proposed method determines the gross weight of the classified object using a pre-determined database. For instance, if an object is classified as a backhoe, the process finds its weight from the database and assigns it as 25,000lbs. Using this weight, the system response time can be calculated. Figure 2 shows an overall pipeline for safety margin assignment.

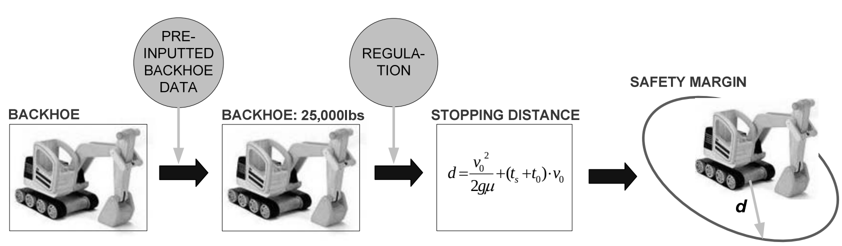

Figure 2 Safety margin assignment

Estimation of proximity to strategic spots or dangerous areas

The proposed method also allows users to define a strategic spot or a danger area within the field of view of the camera. As discussed in the previous section, the strategic spots contain a road curve, a hill point, a road intersection, a road edge (berm), or a dumping edge (berm). The dangerous areas include a specified hazard area, an area between machinery or equipment and the highwall or bank, and an unstable edge of the dumping area. The method first marks such spots and areas. Object tracking and the identification algorithm then keeps monitoring the movement of workers and heavy equipment machinery, and their proximity to the spots or the areas are estimated.

Safety assessment for loading, hauling, and dumping operations

Safety assessment for the loading operation

A loader and a truck are both involved in typical loading operations. The loader scoops material from the stockpile of soil or unformed rock and loads it onto the haulage truck. Since a loading area is generally congested with heavy machinery, different safety rules are applied for 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. Because of these differing conditions, travel and working patterns need to be investigated. Figure 3 shows an example of a typical loading zone for surface mining. In Figure 3, the area near the highwall is regarded as a dangerous working area. The proposed safety assessment method continuously tracks the movement of heavy machinery and estimates their proximity to other machinery and pre-determined dangerous areas to facilitate safety decision-making. The actual loading operation, from the instant that the truck stops for loading to the instant that the truck starts hauling away, is considered to be a safe working condition.

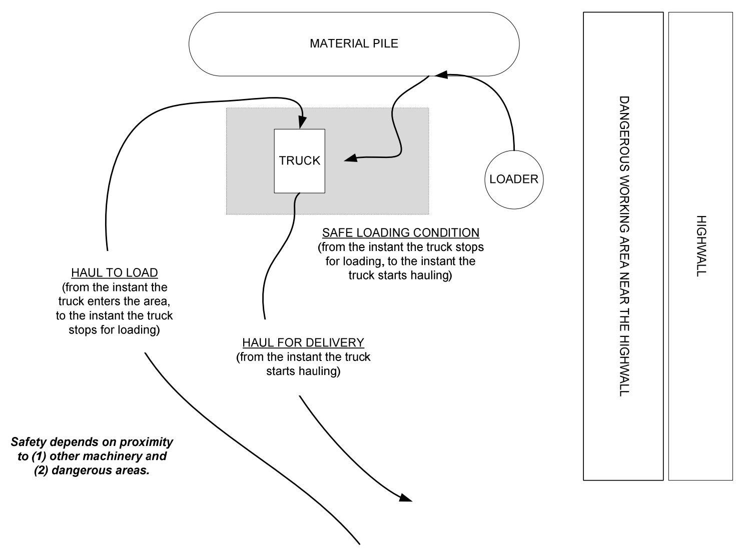

Figure 3 Safety assessments for loading operation

Safety assessment for the hauling operation

The proposed assessment method for the hauling operation first tracks the machine's moving speed, which is one of the most common risk factors of haulage-related accidents. As shown in Figure 4, the method first determines dangerous access spots near the road edge, tracks proximity to these spots, and prevents the truck from traveling through the spots. In addition, the method sets a strategic spot near a road corner, a hill, or an intersection and calculates proximity to the spot in order to help operators have a clear sight distance. The method also estimates the proximity to other trucks and compares it with the calculated stopping distance for safety decision-making.

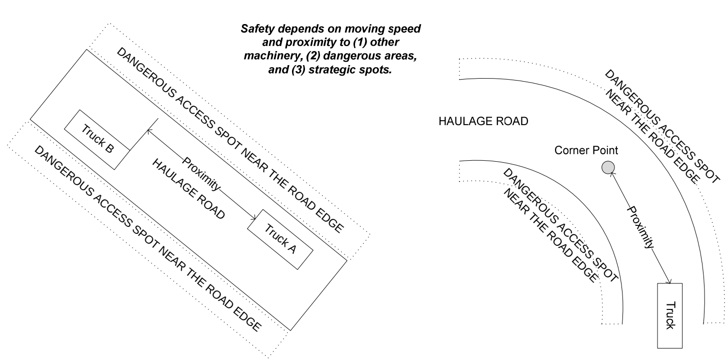

Figure 4 Safety assessment for hauling operation

Safety assessment for the dumping operation

The most common fatal dump-point accidents involve trucks going over the edges of piles. Thus, the proposed assessment method for the dumping operation primarily focuses on the estimation of proximity to the berm near the pile edge (Figure 5). 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 method also monitors proximity to other trucks to avoid collision between machinery.

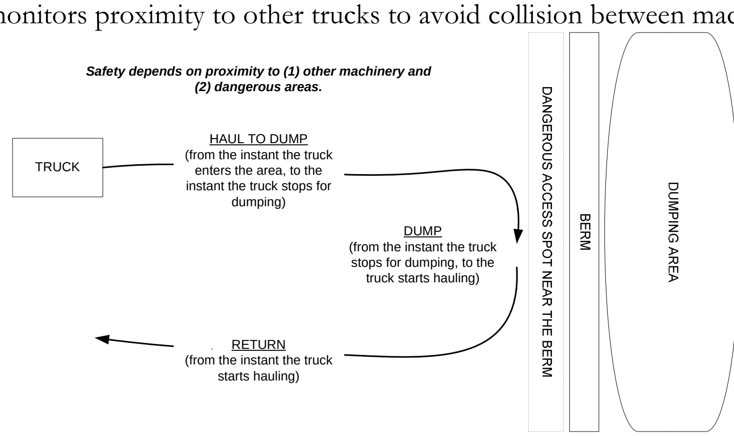

Figure 5 Safety assessment for dumping operation

Preliminary Results

Preliminary experiments were conducted for testing and validating the proposed methods. The algorithm codes were written using the C++ programming language. A laptop computer (3.2 GHz Intel Pentium 4 CPU and 1.5 GB of RAM) was used for program implementation. For analyzing the performance of object identification and tracking, experiments were conducted on an actual construction site, where simple earthworks were performed by a skid steer loader, a backhoe, and a worker. A background subtraction algorithm first extracted the moving objects from an image sequence, and the spatial characteristics of the moving objects were then entered into classifiers (a normal Bayes classifier or a neural network). Using these entered variables, the classifier classified each object as a worker, a loader, or a backhoe. Figure 6 shows examples of the classification results. A total of 1,282 images were analyzed, and the classification algorithm was processed three times per second, which was a close approximation of real-time applications. The overall classification errors of two of the classifiers were under 4% (Bayes classifier: 3.35% and neural network: 3.90%), which showed an acceptable rate of accuracy for the algorithms.

Figure 6 Object identification and tracking: worker, loader, and backhoe

For performance evaluation of the proximity estimation method, outdoor experiments were conducted in a controlled environment using a skid steer loader and a worker at the Field Systems and Construction Automation Laboratory at the University of Texas at Austin. The safety margin around the classified loader was set based on its moving velocity. The proximity estimation process then observed the loader's proximity to the worker when he approached the safety margin determined by the machine's stopping distance. Table 4 shows the estimated proximity between the loader and the worker (distance between two centroids – 3D worker width/2 – 3D loader width/2) and the calculated stopping distance. Since the worker first approached the moving loader and then moved away from the loader, the proximity between two objects decreased first and increased again. When the proximity was smaller than the stopping distance as shown in Table 4, we might say the worker was within the dangerous distance from the operating loader.

For proximity estimation to dangerous areas, the restricted area was manually pre-determined, and the proximity estimation method observed access area violation to when tracked object approached the area. All actual violations were identified. The method determined that the worker crossed into the danger area 22 times over the course of the overall 50 captured images, and the loader entered it 13 times over 41 images.

Table 4 Performance analysis of proximity estimation

Frame	Distance b/w centroids(m)	Worker width (m)	Loader width (m)	Proximity (m)	Loader vel. (m/s)	Stopping distance (m)
1	3.70	1.46	4.39	0.77	0.50	0.79
2	3.02	1.32	4.70	0.11	0.48	0.77
3	2.90	1.04	4.65	0.06	0.46	0.72
4	3.16	1.82	4.05	0.23	0.47	0.74
5	3.70	1.69	4.32	0.70	0.51	0.80

Conclusions

This paper presents an ongoing research project concerning the development of an automated safety assessment framework for earthmoving and surface mining activities. Preliminary results showed the feasibility of proximity estimation as well as object identification and tracking, which can be used for automated safety assessment in future research. In order to evaluate the performance of the entire safety assessment process, experiments on an actual surface mining project are in the planning stages. Dangerous areas and strategic spots will be first identified and assigned at loading, hauling, and dumping sites, and the proximity to these areas and spots will then be monitored in 3D for safety decision-making. The proximity of on-site objects to each other will also be estimated, and these distances will be compared with the stopping distances of the machinery. Last, information of static objects on sites can be pre-inputted into the process so as to achieve more robust safety decisions.

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