Automatic Fall Risk Identification using Point Cloud Data in Construction Excavation

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ABSTRACT

Safety continues to be among the top issues in the construction industry after experiencing 775 fatalities in 2012. Among all those fatalities, fall has been considered as one of the leading contributors for several years. This paper presents a method that automatically identifies fall risks on construction sites under excavation by utilizing laser scanning technology. It first extracts safety rules that are related to fall risks from OHSA standards and construction best practices. Then, it collects sets of point cloud data of a construction site under excavation using laser scanning, registering and cleaning the point cloud data afterwards. Finally, it develops an identification algorithm based on those rules and applies the algorithm onto the data to identify potential fall risks by analyzing geometrical properties. An experimental trial is also conducted in this paper and results show that the method successfully identifies those fall risks. The presented method can actively monitor the fast changing situations of construction sites under excavation and provide inspectors and project managers with valuable information about fall risks, helping them make good safety decisions and prevent fall accidents and fatalities.

INTRODUCTION

Fall has been considered as one of the leading contributors of construction worker fatalities for several years. It continues to plague the construction industry, despite the establishment of relevant safety regulations and the availability of protective systems. Out of 775 worker fatalities in the private construction industry in calendar year 2012, 280 or 36.1% were caused by falls, which is far beyond the second contributor of 10.1% (CFOI, 2003-2012). As these statistics indicate, fall risk remains a big problem and we need to take further actions to prevent them.

In the construction industry, the identification and assessment of critical safety issues often involves the experience and judgment of field personnel, such as safety inspectors. However, the diversity of accidents and their repetitive nature may result in the fact that proper inspection of construction sites is often not accurately performed or safety inspectors are absent when needed (Teizer 2008). For these reasons, a method for the automated identification of construction excavation safety risks is needed.

This paper presents a method that automatically identifies fall risks in construction excavation by utilizing laser scanning technology. It first extracts safety rules that are related to fall risks from OHSA standards. Then, it collects sets of point cloud data of a construction site under excavation using laser scanning, registering and cleaning the point cloud data afterwards. Finally, it develops an identification algorithm based on those rules and applies the algorithm onto the data to identify potential fall risks. The presented method can actively monitor the fast changing situations of construction sites under excavation and provide inspectors and project managers with valuable information about fall risks, helping them make good safety decisions and prevent fall accidents and fatalities.

BACKGROUND

The Current Research of Fall Risks. A safe and healthy working environment is mandatory in the construction industry. Lots of research has been conducted on construction fall safety to achieve that goal. Huang and Hinze particularly studied construction worker fall accidents and their results showed that fall accidents accounted for a growing proportion of the total number of construction worker fatalities (Huang and Hinze 2003). Very recently, Zhang et al. developed a ruled based checking method on automatic fall risk identification in construction models based on Building Information Modeling (Zhang et al. 2013).

However, there is very limited amount of research on fall risks in construction excavation, especially on automatic technology-aided fall risk identification in construction excavation. Currently, excavation fall safety inspections rely on frequent manual observations by the competent person required by OSHA standards, making the inspection a labor-intensive and error-prone task. Besides, the complex and dynamic nature of construction excavation makes safety inspections during excavation very challenging. The most severe consequence of improper safety inspection is worker fatalities. Technology-aided inspections, therefore, can be applied on a daily basis during the whole excavation period to keep dynamic track of the jobsite under excavation.

Laser Detection and Ranging Technology. Laser detection and ranging (LADAR, also known as laser scanning) is one of the technologies that have been broadly utilized for the research of construction, especially construction safety and health. Most recently, Marks et.al used laser scanner and gathered blind spot of several heavy equipment, to provide design suggestions that increase operator visibility (Marks et al. 2013).

3D terrestrial laser scanning is a promising geometric data collection technology for construction and measures the distance from the sensor to nearby objects, providing point cloud data with fast sampling rate and millimeter level accuracy (Tang et al. 2009). Such data would enable the accurate geometric assessments of as-built jobsite conditions as to automatically and actively identify daily changing safety risks.

RESEARCH OBJECTIVE AND FRAMEWORK

The objectives of this research were to automatically identify and visualize fall risks on a construction excavation site with the help of laser scanning technology. The proposed framework of this research is shown in Figure 1.

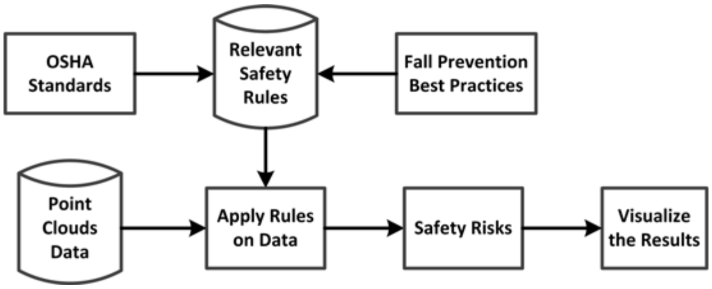

Figure 1 Framework of automatically identifying and visualizing safety risks

EXTRACTING RELAVANT SAFETY RULES

For fall protection, OSHA requires that employees walking/working on surfaces with an unprotected side or edge which is 1.8 meter or more above a lower level should be protected from falling by using protective systems such as guardrail system, safety net systems, and so on (OSHA). This rule is generally followed by most construction fall prevention best practices, so we are going to abide by the same rule in this research. Further rules can be applied by the safety inspector if needed.

APPLYING RULES ON DATA

This section presents detailed procedures for the process of applying previous safety rules and automatically identifying and visualizing fall safety risks. A flowchart of research methodology is illustrated in Figure 2. This research utilized Matlab^{TM} to develop the algorithms for data processing.

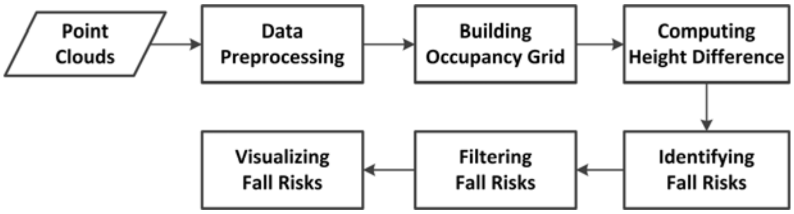

Figure 2 Flowchart of automatically identifying and visualizing fall safety risks

Data Preprocessing. Data preprocessing contains two processes: point cloud data registration and point cloud data cleaning. The registration process puts together multiple scans collected by a commercially-available laser scanner into a global coordinate system, enabling the full geometrical information of the construction site. The cleaning process removes unwanted data such as mixed pixels and points caused by moving objects prior to downstream process (Tang et al. 2009). This process can be either performed on the level of individual scan or after all scans of point cloud data have been registered. The presented algorithm in this paper does not require or focus on the automation for registration or cleaning. So we will manually aid the registration and cleaning processes in this research.

Building Occupancy Grid. The registered and cleaned point cloud data will then be exported into a xyz file and stored as an N x 3 matrix where N is the total number of points and the three columns represent X, Y and Z coordinate for each point respectively. Based on the geometrical information, we build up a three-dimensional occupancy grid along the X, Y, and Z axis by computing a bounding box of the dataset (Cheng and Teizer 2012 Teizer et al. 2007). The grid has multiple user-defined size cubic units called cells (or voxels, volume pixels) and range points falling within a cell's coordinates are considered to be inside that particular cell. A cell with no inside range points is an empty cell and empty cells will not be processed in any downstream process of the algorithm, analyzing detailed geometrical properties of each cell. Using the methodology of building occupancy grid makes the algorithm computationally much cheaper since most (more than 90%) of the cells are empty and they will no longer be processes in future.

Computing Height Difference. According to the previously extracted rules, we only consider height different for the identification of fall risks. Procedures for computing the height difference of each column are shown in the following three steps

(1) For each of nonempty cells, compute the following cell properties: index location for the cell (<X Index>, <Y Index>), coordinates for the center of the cell (<X Center>, <Y Center>, <Z Center>), maximum of Z coordinates among all range points within the cell (<Z Maximum>), minimum of Z coordinates among all range points within the cell (<Z Minimum>) and have them stored as an M x 7 (M is the number of nonempty cells) matrix ;
(2) Add up cells with same <X Index> and <Y Index> into columns and compute the maximum of Z coordinate (<Z Max Column>) and minimum of Z coordinate (<Z Min Column>) for each column by taking the maximum of <Z Maximum> and the minimum of <Z Minimum> for all the cells inside that column;
(3) For each column, compute the height difference by:

$$< \text{Height Difference} > = < \text{Z Max Column} > - < \text{Z Min Column} >$$

Identifying Fall Risks. The identifying process of fall risks is straightforward that if the <Height Difference> for a particular column is 1.8 meter or more, that column is temporarily recognized as having fall risks. However, two general exceptions need to be caught before we precede the algorithm and we generate a filtering algorithm to remove those unwanted exceptions from the next several steps.

Filtering Fall Risks. The filtering process basically handles two types of exceptions shown in Figure 3 and Figure 4 respectively.

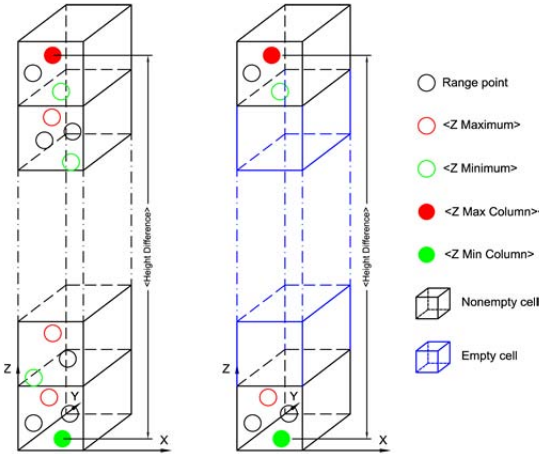

Figure 3 Illustration of algorithm for filtering the first type of exception

Figure shows the first exception that the right column has only two (or not enough) nonempty cells inside, and all other cells within the column are empty. Although the height difference of this column happens to be greater than 1.8 meter, it should not be considered as real fall risk since it presents no falling hazards to construction workers in reality. This situation can occur either because of improper previous cleaning process or extrusions on vertical cliffs in real construction environment, but the protective systems are needed in neither case. Columns identified as hazardous due to this exception should therefore be filtered as follows.

- For each column that has been temporarily recognized as having fall risks, if the number of nonempty cells within the column is less than a threshold, we consider it to be safe but not hazardous. Recall that the size of the cell has been previously defined by the user, the threshold can be therefore calculated by:

$$< Threshold >= \frac{1.8}{size\ of\ cell}$$

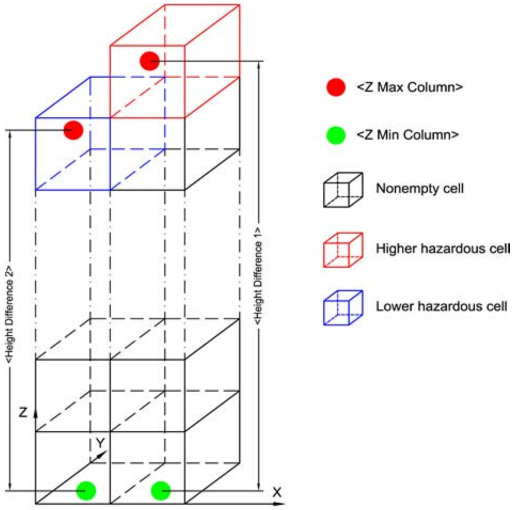

Figure 4 Illustration of algorithm for filtering the second type of exception

Figure 4 shows the second exception that two columns are next to each other and the <Height Difference>'s for both columns are of 1.8 meter or more. If the number of nonempty cells in both columns happens to be greater than the threshold we just set, then both columns would be identified as fall risks. However, only one of them should be considered as fall risk since it does not help in reality to use protective systems for both places which are so close to each other. Finally, we choose to consider the higher column as real fall risk that needs the protective system for the following two reasons: 1) apply protective system to the higher column can prevent construction workers from falling to the lower hazardous cell if their height difference is also very large (not the case shown in Figure 4) and 2) construction workers usually do not need to reach the lower column since most areas with width of only 0.3 meter are not reasonable working surfaces on real construction site. This exception can be filtered by the following steps.

- For each column that is still recognized as fall risks after first filtering, consider its surrounding four columns. If any of those surrounding columns is also still recognized as fall risks and is higher than the current one, we consider the current lower column be safe but not hazardous.

The remaining columns still recognized as fall risks are the final outcomes identified to be hazardous. Figure 5 illustrates the algorithm for fall risks in flowchart.

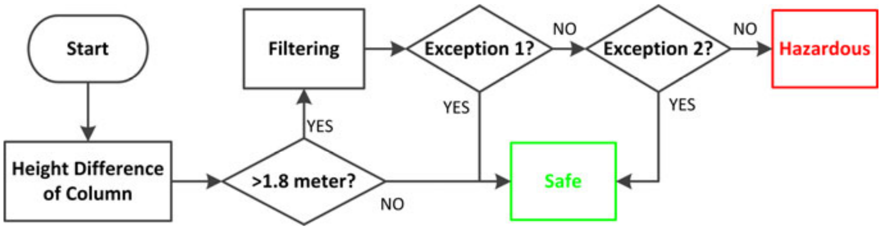

Figure 5 Flowchart of algorithms for identifying fall risks

Visualizing Fall Risks. The above identified fall risks are visualized by the following rules. The top first nonempty cell of each hazardous column will be marked red because it is usually the place where construction workers may fall and protective systems are needed. All other nonempty cells will be marked green. Empty cells are not visualized.

EXPERIMENTS AND RESULTS

The site for Engineered Biosystems Building (EBB) at Georgia Institute of Technology, Atlanta was selected to validate the identification algorithm. The size of the site was approximately 120m x 80m and the deepest part of the excavation was more than 8m. At the time of the experiment, protective systems had been used for some part of the site. Four scans were conducted to ensure the full geometric information of the site. The view of the construction site after registration and cleaning is presented in Figure 6, where four white circles indicate the location of the laser scan station for each scan.

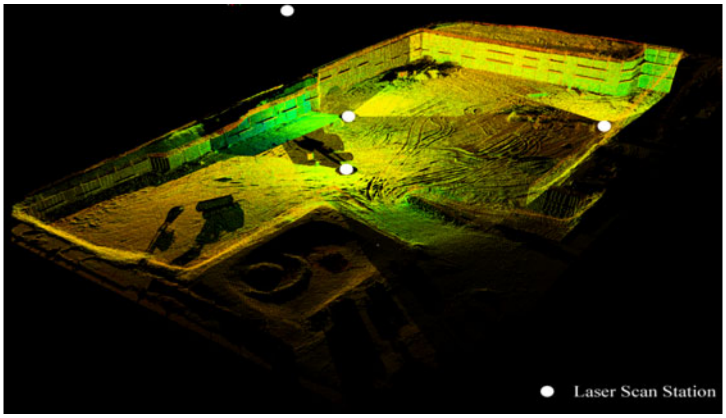

Figure 6 View of the construction site after registration and cleaning

We then built up a three-dimensional occupancy grid for the data, consisting of multiple cubic cells. Depending on the scale of the construction site and level of computational complexity, the size of cell was defined as 0.3m x 0.3m x 0.3m and it can be adjusted from case to case. A total number of 4,444,000 cells were constructed while only 125,013 of them are nonempty.

For each nonempty cell, we compute the previously mentioned geometrical properties and have them stored in a 125,013 x 7 matrix. Then we add up cells with same <X Index> and <Y Index> to build up columns as to compute the height difference of each column. If the height difference of a column is 1.8 meter or more, we temporarily consider that column to be fall risks. The filtering algorithm is then applied to catch exceptions. Notice that the threshold is calculated by <Threshold> = 1.8 meter / size of cell, so the threshold is 6, which means that if the number of nonempty cells within a particular column is less than 6, it should be considered as safe. After two types of filtering, columns that are still considered to be fall risks will be visualized. Figure 7 shows the visualization of the outcomes for fall risks identification. In Figure 7, we marked the top first cell of each identified column to be red and all other cells to be green. Empty cells were not visualized.

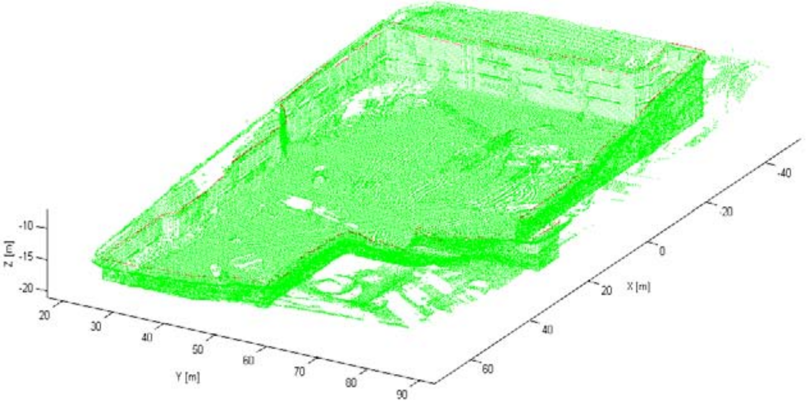

Figure 7 Visualization of fall risks identification outcomes

CONCLUSION

The presented method in this research automatically identifies and visualizes fall risks in construction excavation. As the outcome shows, it generates meaningful figures to construction managers, plotting areas where protective systems are needed with a different color. The potential contributions of this method are in two-fold: creation of realistic safety inspection map and reduction of manual efforts.

However, one main limitation needs to be overcome in order to realize the full potential of the proposed method. The proposed method computes the vertical height difference within the tolerance of a column. It may not work in the situation that the 'vertical' surface is not very steep so that the height difference of any area within a column satisfies the rule, but that of the whole surface does not. A larger column size could be considered to generate more realistic outcomes. But large amount of research needs to be conducted to specify the slope of vertical surface that has potential fall risks on the regulation level.

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