Vision-based Tracking of Worker Trajectories in Built Workplaces for Safety and Health Study

by

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ABSTRACT

Construction sites are the place where personnel and equipment work closely. In such workplaces, human movement dynamically adapts to the surrounding circumstances which are congested and continually changing. Acquisition of worker trajectories and measurement of physical value of workplaces, however, typically requires on-site investigation, and thus is a time-consuming and error-prone process. Insufficient understanding of manual tasks and working environments in terms of operational planning and analysis can lead to unreasonable work plans, irrational layout design of the workplace, and unsafe equipment operation. As a result, workers are facing risks caused by adverse jobsite conditions. Accordingly, the purpose of this research is to improve worker health and safety on construction sites through designing a safer workplace, eliminating potential injuries caused by unhealthy motion, and reducing risks of equipment operation. Specifically, stereo videos are collected by a stereo vision camera to record the dimension of construction workplaces and also to record worker movements. Then the depth information contained in the stereo videos are analyzed and processed (e.g., computing disparity from stereo videos and reconstructing 3D scenes from a disparity map) to quickly extract worker trajectories and to accurately rebuild 3D models of workplaces. The acquired geometry information of worker movements and workplace models can assist personnel in designing better project plans to facilitate the following three aspects: (1) providing necessary inputs for motion study to design a healthier motion plan; (2) providing a visible 3D model of workplaces to

recognize unsafe workplace layouts; and (3) enabling operators to identify potential risks and hazards during equipment operation and then achieve safer equipment operations.

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CHAPTER 1. INTRODUCTION

1.1 Research Motivations and Problems

The construction industry has a high injury rate, an adverse situation that continually demotivates construction workers and also disrupts the construction process. The construction industry is high risk due to congested working areas, repetitive work, equipment operations, etc. (Choudhry & Fang, 2008). The National Safety Council in the United States (1997) reports that in 1996 alone, 1,000 construction workers lost lives, and more than 300,000 workers received serious injuries. The Occupational Safety & Health Administration (OSHA, 2016) reports that 4,386 workers were injured in 2014. In Canada, the Association of Workers' Compensation Boards of Canada (AWCBC, 2012) also reports that the construction industry was responsible for the majority of industry fatalities that occurred in 2012 (shown in Figure 1-1). Ostensibly, the construction industry statistically continues to be one of the most dangerous occupations compared with other industries.

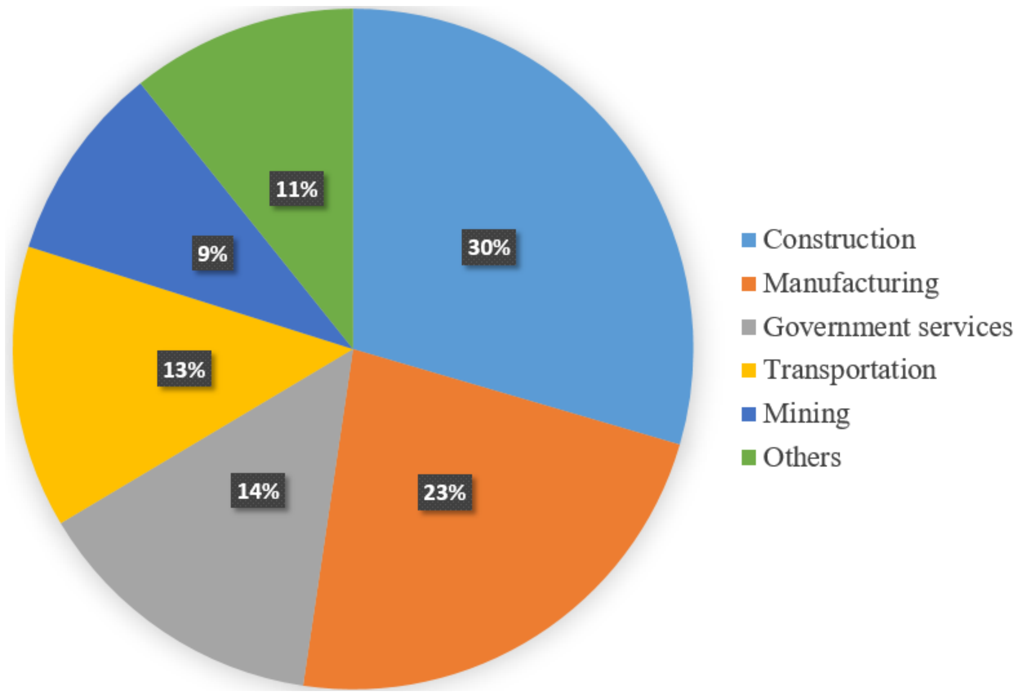

Figure 1-1: Canada's most dangerous industries: fatalities.

Current safety precautions for construction workers in the industry comprise more than requiring construction workers to wear safety helmets on jobsites. Rather, it is a field which studies ways to effectively identify the various types of risks and hazards on construction jobsites and then develop methods to eliminate them.

It should be emphasized that nearly all injuries and illnesses that occur in the field of construction are preventable (Ringen et al., 1995) because the safety and health problem is closely related to the organization of construction projects and how manual tasks are performed. Most risks in the construction industry actually result from insufficient communication of site information and inadequate measurement technology (Ringen et al., 1995). Therefore, if sufficient and adequate information of workplaces and manual tasks is provided, the safety and health performance will be significantly improved. Based on the statistics of construction accidents, the majority of injuries in recent years result mainly from three aspects: (1) unsafe site layout, (2) unhealthy worker motions, and (3) unsafe equipment operation (OSHA, 2016).

First, the constantly changing working environment has significant effect on safety and health. Extensive movements by construction workers from location to location are necessary to complete projects on construction sites (Ringen et al., 1995). Environment planning, more specifically site layout planning in the construction industry, is considered a proven tool for reducing the impacts from environmental risks but has been largely overlooked by site engineers (Sanad et al., 2008). Site layout planning or organization is of great importance, which should be sufficiently considered as early as possible in the construction planning stage. However, in many previous studies, site layout planning has been specifically focused on optimizing site objects for productivity reasons rather than given enough consideration for safety and health issues (Anumba & Bishop, 1997). The construction industry has a poor safety record when compared with other industries. A large amount of time and money is lost due to work-related health problems. There are numerous factors which lead to these work-related problems (i.e., worker injuries and fatalities) on construction sites such as falling objects, site conditions, collapse of site structures, overturning of site structures, site transportation, hazardous substances, and poor monitoring of site activities.

Additionally, construction sites are busy places with continually changing working environments, which makes it is very difficult to predict potential risks before and during construction (Bansal, 2011). The above mentioned factors comprise the unique nature of the construction industry; however, it should be noted that some of the causes of construction site accidents (i.e., site transportation, falling objects, and hazardous substances) can be eliminated through better site layout planning (Anumba & Bishop, 1997).

One major aspect of construction site layout planning involves identifying the proper position of construction facilities on jobsites because it impacts the safety of construction operations. Site layout planning includes temporary and permanent (or fixed) facilities layout planning. Temporary facilities are those that serve the construction site but will be moved and dismantled after a period of time. The construction site layout problem involves identifying the number and size of construction facilities, finding constraints among facilities, and then locating and dimensioning construction support facilities (Zouein et al., 2002). For example, the locations of the material storage areas, site office, and fabrication yards all need to be considered by planners (Osman et al., 2003) since these facilities usually exist during construction projects. It is known that an efficient overall site layout plays an important role in terms of cost, efficiency, and quality of construction projects; however, an efficient layout plan cannot always be reached because different participants (i.e., owners, contractors, and workers) have their own interests. A site layout plan is usually performed by construction managers. Therefore, managers need to arrange the facilities based on the needs of different parties. It should be mentioned that most projects managers learn site layout planning through experience and common sense (i.e., trial and error in years of fieldwork) (Sanad et al., 2008).

To conclude, the site layout plan problem can be regarded as an optimization problem. In practice, the most important question for engineers is how to minimize the inter-facilities transportation cost. The equation commonly used to calculate the transportation cost is shown below (Sanad et al., 2008). In this formula: n means total number of construction facilities; d_{ij} means the distance between facility i and facility j; and R_{ij} means the transportation cost for traveling between the facility i and facility j. Although the available models are able to minimize the travel cost of on-site resources, these models have not considered safety as an essential factor when optimizing the construction site layout. It can be easily seen from the most commonly used formula below, no parameter in this formula is related to safety and health consideration. Therefore, there is a need to present a new site layout planning model which is capable of minimizing the travel cost of construction facilities and ensuring at least a satisfactory performance of construction safety.

$$Min \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} dij\, Rij$$

The other aspect of construction site layout planning involves another reason for causing risks and dangers in construction sites: the information exchange is not efficient or convenient. Specifically, reasonable layout plans cannot be applied to construction sites because the site information is recorded in different ways. For example, engineers prepare the drawings for construction sites while contractors describe the project by contracts, and managers take notes to record updates on construction jobsites (Cheng & O'Connor, 1996). All of these methods hinder the speed of information exchange. If a method capable of speeding up the exchange of information is introduced, the different parties in a construction company can better understand the needs of others, resulting in better communication among them, and the possibility of applying safer construction plans to the construction projects.

Second, work-related musculoskeletal disorders (WMSDs) are one of leading causes of occupational injuries in the construction industry (Golabchi et al., 2015). Specifically, WMSDs are responsible for about 34% of nonfatal injuries (CPWR, 2013); compared with other industries, workers in the construction industry are more likely (approximately 50% higher risk) to suffer from WMSDs (Schneider, 2001). As a result, increased health care and compensation costs for disabled workers are invested in construction companies (Valsangkar & Sai, 2012). The annual cost of WMSDs to the Canadian economy is approximately $20 billion (McGee et al., 2011). The construction industry is by nature labour-intensive; therefore, it is difficult to avoid workers being exposed to manual tasks with forceful exertion and awkward postures

(Golabchi et al., 2015). Additionally, considering the presence of heavy equipment, physically demanding tools, and changing work environments, the jobsites in the construction industry are more risky and dangerous (Abudayyeh et al., 2006). Currently, construction companies focus more on improving productivity over ensuring safety and health of construction workers such as conducting ergonomic analysis (Freivalds & Niebel, 2013). As a result, project managers should be made aware that the economical outcome of increased productivity may be offset by the increased medical and compensation costs caused from WMSDs when ergonomic analysis is not sufficiently addressed by construction companies (Golabchi et al., 2015). The planning stage is of great importance because it is the phase when engineers design how construction projects work in detail. Therefore, this phase (i.e., planning stage) offers the opportunity to take preventive measures; by considering safety problems (e.g., occupational health risks), most accidents can potentially be avoided (Weinstein et al., 2005; Nussbaum et al., 2009).

In the construction planning stage, one of many popular ergonomic methods to eliminate workers' WMSDs on construction jobsites is motion analysis. Specifically, motion study is the study that analyzes human action while performing manual tasks, by means of which, the potential health risks can be identified (Guo et al., 2016). However, worker motions significantly adapt to surrounding circumstances. Also, constantly moving workers and rapidly changing work environments require a significant amount of time and effort to carry out on-site investigation such as measuring trajectories and physical surroundings (Golabchi et al., 2015). Therefore, the current challenge is how to obtain such trajectories and physical information in a timely and accurate manner.

Third, equipment operation on construction sites is also a major source of construction accidents and injuries. The construction site is the place where different construction resources work interactively. When construction equipment is moving closely around ground construction workers, potential risk is created such as contact collisions between construction workers and heavy construction equipment (Marks & Teizer, 2013). The interactions between workers and heavy equipment can easily create visibility-related injuries to workers. Therefore, worker safety and health cannot be guaranteed. OSHA (2002) reports that more than 50% of total fatalities were caused by “struck-by” accidents, “caught-in” accidents, and electronic shock, and the operation of construction equipment is responsible for the majority of fatalities in these three types of accidents. In 2009, the Bureau of Labor Statistics reported that 18% of total fatalities (151 of 818 fatalities) are related to construction equipment. Current safety practices to prevent equipment-caused accidents require construction workers to wear passive safety devices such as a safety helmet or other personal protective equipment (PPE). However, in some cases such as the contact collision between ground construction workers and large construction equipment, a simple helmet cannot protect workers from injury. Through safety training and education, the construction company intends to increase construction workers’ safety and health awareness; however, under certain circumstances, construction workers still face risks. For example, when some unforeseen delays occur during the construction process, the workers could perform faster but unsafe and unhealthy methods in order to complete the construction tasks on time.

Basically, the reasons for equipment-caused accidents can be summarized by two aspects: (1) the operator's field of view, reaction speed, and depth perception are limited because of blind spots in construction sites, and (2) the construction site is a changing environment (Kim et al., 2006). Traditionally, construction equipment is controlled by human operators. However, workers are prone to make more mistakes than robots. Therefore, better safety and health performance can be achieved when there is less reliance on human effort and decision-making. Considering the technology advancement in recent years, the use of a computer-assisted system should be taken into account as it can potentially perform well when sufficient inputs are available. Therefore, it is necessary to develop an approach to offer accurate information for equipment operation in order to achieve obstacle avoidance.

For construction safety and health, much research effort has attempted to evaluate and improve safety performance. Based on the literature review, however, limitations still exist. Specifically:

1) Construction site layout planning and organization.

Static layout planning is one current approach commonly used in the construction industry. By using this approach, only one construction site layout plan is planned and then used for the entire project duration. As a result, the site layout plan generated by the static approach will become less usable as the project progresses because the construction sites are continually changing. The other approach is dynamic layout planning. Many researchers have developed their own methods based on the dynamic layout planning. For instance: (1) Zouein & Tommelein (1999), based on dynamic site layout planning, create a sequence of layouts that occur throughout the entire project duration. However, this method can only represent the facilities as rectangles, which is a distortion, compared with real facilities. (2) Li & Love (1998) develop a genetic model capable of minimizing the total travel time and distance among facilities by allocating predetermined facilities to predetermined places. But, the size of the predetermined location can hardly fit the area required by a facility. (3) Cheng (1992) combines the geographical information system (GIS) and the database management system together to solve the problem of site layout planning; however, GIS is functionally limited because of the poor signal in indoor construction sites.

2) Motion study of construction workers.

Alwasel et al. (2011) develop a method which employs sensors to measure body joint angles and identify unsafe postures. David (2005) utilizes worker diaries, interviews, and questionnaires to collect information based on physical and psychosocial factors about worker motions. Han & Lee (2013) develop a computer vision-based approach to acquire worker motions from video to detect unsafe postures. NIOSH (2014) asks analysts to observe working posture and movements through on-site investigation or videos to identify unhealthy and unsafe actions. All of these well-developed methods only study how to analyze ongoing tasks to prevent WMSDs.

3) Construction equipment operation.

   In regard to the safety problem of construction equipment operation, laser is employed because of its high accuracy of data and high signal update rate. It, however, is not able to distinguish a ground worker from other objects. Magnetic marking fields can allow the laser to easily distinguish ground workers from other objects, hence are used in construction equipment operation. But, in practice, these fields require a system specific battery power source, which is difficult to achieve in some construction sites. Sonar is susceptible to elements in the construction environment. Radar can supplement the videos recorded in construction sites although it is not capable of distinguishing ground workers from other objects. Therefore, a new approach that can improve on the above mentioned shortcomings needs to be developed.

To conclude, the research motivations of this thesis generally stem from the above mentioned shortcomings of present methods and also from realizing that the nature of construction sites is a continually changing environment. This research is built on developing an understanding of the construction environment to improve the safety and health performance in the construction industry.

Planners need a tool, by means of which the changing environment can be truly understood and then the level of both safety and health can be improved. Accelerating advances in information technology (IT) could be used to help planners at the planning stage to complete the decision making process by offering them up-to-date construction site information. The research presented in this thesis employs a 3D reconstruction approach with the potential to streamline the process of obtaining worker trajectories and geometry information of workplaces, which enables facilities layout, manual tasks, and equipment operation to be better designed.

1.2 Research Objectives

1) Problem statements

   The injuries and fatalities that frequently occur on construction sites continue to be a problem that requires attention. Based on the available statistics, it can be seen that construction accidents are mainly resulted from unreasonable construction site layout planning, unhealthy worker motions, and unsafe construction equipment operation. The accidents caused by these three conditions are due to the lack of understanding of the personnel at the project planning stage surrounding the changing construction environment. Therefore, an approach which is able to capture the detail of construction workplaces has the potential to improve current safety and health performance. However, existing approaches have their own limitations as mentioned above.

2) Approach

In this research, the 3D reconstruction approach is adopted and developed due to its ability to timely and accurately capture the detail of construction activities occurring on construction jobsites, which will provide sufficient information for site layout planning, motion study, and equipment operation.

3) Hypothesis

3D models of built environments and motion trajectories can be extracted from and built with stereo cameras, which can later be used for health and safety analysis. To this end, stereo videos recorded by stereo cameras are used to analyze the depth information of objects in the scene. Then the point cloud data can be rebuilt based on the result of depth analysis; the point cloud data can also provide useful information for the purpose of safety and health improvement. Specifically: (1) detailed dimension information of construction workplaces can be obtained in order to carry out site layout planning at the project planning stage; (2) trajectories of construction workers can be extracted for motion study; and (3) equipment operation can also benefit from better understanding the changing construction jobsites.

4) Objectives

- To prove that the stereo video-based reconstruction approach has the ability to capture changing working environment and moving construction workers. To this end: First, 3D models of working environments are rebuilt by using stereo vision cameras. The stereo vision camera is employed in this research to record stereo videos for construction sites and construction workers. Then the recorded videos will be processed through the 3D reconstruction approach to rebuild the point cloud data of the construction environment and construction workers. Second, the geometry information contained in the point cloud data will be measured and also tested. For example, the dimension of workplaces and moving distance of workers are extracted.
- To better design site layout, eliminate risks of human motion when performing manual tasks, and safely operate equipment. Based on the geometry information of the working environment and trajectories of construction workers, personnel at the project planning stage are able to have a better understanding of construction jobsites and the exact ways that construction workers perform manual tasks. The information can then be analyzed to determine if any change should be made to adjust the working environment and manual tasks in order to create a safer working environment.

1.3 Thesis Organization

This thesis is organized into five chapters.

Chapter 2 (Literature Review) provides a summary of the current situation of worker health and safety in the construction industry. In addition, the existing and potential applications of computer vison are introduced.

Chapter 3 (Proposed Methodology) presents the proposed methodology used in this research. The type of data and the device are described. Then the detailed methods for tracking worker movement and reconstructing workplaces are discussed.

Chapter 4 (Experiment of Reconstructing Models and Tracking Trajectories) proves that the proposed method can generate accurate 3D models of environments and trajectories which can be used for site layout planning, motion study, and equipment operation.

Chapter 5 (Discussion on Conceptual Applications) discusses the application of the proposed method in a fabrication company. Chapter 5 illustrates the potential of the proposed method to facilitate site layout planning, to offer inputs for motion study, and to promote improved equipment operation.

Chapter 6 (Conclusion) describes the general conclusions, contributions, current limitations, and future research.

CHAPTER 2. LITERATURE REVIEW

The purpose of this literature review is to understand the current state of knowledge about the safety issues and corresponding methods used in the construction industry. There are four topics to discuss in this chapter. First, safety issues caused by unreasonable site layouts and existing methods are discussed. Second, human injuries caused by unhealthy motion are discussed. Third, the accidents caused by unsafe equipment operation and existing approaches are discussed. Finally, the potential ability of computer vision technology to solve the above mentioned safety and health problems is explained.

2.1 Safety and Health in the Construction Industry

In this section, safety issues related to layout planning, motion study, and equipment operation are reviewed. Also the existing methods and their shortcomings are discussed.

2.1.1 Workplace Layout-caused Issues

2.1.1.1 Background of site layout planning

The effective and efficient management plan of site layouts is the essence of success for ensuring worker safety and health during any construction project. However, the dynamic nature of construction projects has made the site layout process complicated. Also, space requirements and site constraints vary along the project's progress (Osman et al., 2003). Site layout design can be regarded as a complex optimization problem of allocating a set of facilities (Osman et al., 2003); however, site layout design involves many planning constraints which are difficult to optimize (Sanad et al., 2008). Basically, the problem of workplace layout design includes two main aspects. Solving these two design problems can improve worker safety and health in construction factories. Figure 2-1 (Choi & Flemming, 1996) shows the time phase at which the layout planning should be carried out.

- Layout design of temporary facilities.
- Layout design of permanent facilities.

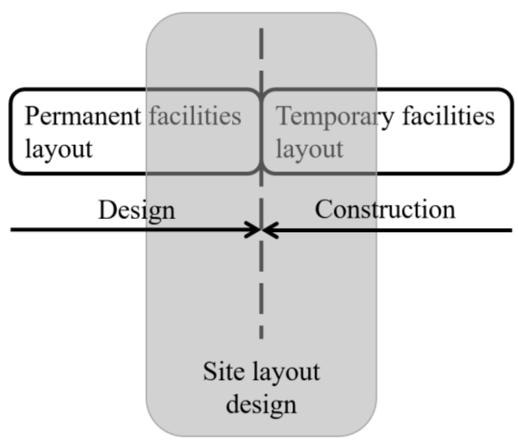

Figure 2-1: Phase of site layout planning.

Temporary facilities are those located on jobsites to serve the purpose of supporting permanent facilities or supporting construction operations (Sanad et al., 2008). Temporary facilities (e.g., warehouses and disposal bin for leftover steel) can help optimize workforce travelling, material handling, equipment controlling, etc. One primary concern of layout design is to identify which area is suitable to accommodate the temporary facilities. Theoretically, considering the convenience, temporary facilities are usually located near their support activities in order to reduce travel time. But, in reality, every facility on construction sites has a very interactive relationship with other tasks (Cheng & O'Connor, 1996). In other words, in a construction company, different parties such as general contractors and engineers have their own priorities, interests, or concerns. Therefore, conflicts inevitably exist and are difficult to address.

Additionally, the information available for layout design of temporary facilities is often insufficient and ill-structured, this occurs because drawings of site layouts cannot be updated frequently (though the environment continually changes) and different parties store information in different ways (Cheng & O’Connor, 1996). For example, engineers prepare the drawings graphically, while construction schedules are prepared in bar charts, and contracts are written in words (Cheng & O’Connor, 1996). All of these will lead to unsafe layout, thereby generating risks to workers.

Permanent facilities (or fixed facilities) are those positioned in a fixed location (Hegazy & Elbeltagi, 1999). When planning permanent facilities, planners must consider minimum distance, safety zones, etc. Otherwise, permanent facilities can also create safety and health issues to workers.

Usually, in current construction industry, two approaches are adopted to carry out site layout planning. The first approach is static layout planning. This approach prepares only one site layout which is expected to be used for the entire project duration. However, considering the changing nature of any construction site, the site layout generated by the static approach will become obsolete as the project progresses. The other approach is called dynamic layout planning. This approach differs from the static site planning because it creates several site layouts which consider the change in site conditions (Drira et al., 2007). One important factor that needs to be considered in site layout planning is transportation cost. However, these site layout plans are created prior to the construction phase. Therefore, the employment of Proximity Weights (PW) is necessary to estimate the desired closeness between any two facilities (Osman et al., 2003). These proximity weights are determined by fuzzy set theory. Basically, it works as if two facilities are required to be located closely, then a high proximity weight is assigned to make them close in the optimization process and vice versa. Zouein & Tommelein (1999) adopt dynamic site layout planning to propose a model used for construction facilities. They create a sequence of layouts that occur in the entire project duration and utilize linear programming to find the optimal position in order to reduce travel time. However, this method can only represent the facilities as rectangles, which is a distortion, compared with real facilities.

In order to solve these problems, many other research efforts have been developed. For example, Elbeltagi et al. (2004) develop a model which takes safety and productivity into consideration. Constructed space is used to analyze the congestion level in restricted construction sites. Then, a greater negative value can be assigned to the closeness when there is a safety issue between two facilities, which improves the layout plan. Li & Love (1998) develop a genetic model to solve the problem. This model is capable of minimizing the total travel time and distance among facilities; in order to do this they allocate predetermined facilities to predetermined places. But the problem is how to ensure that the size of predetermined locations fits the area that a facility actually needs. Cheng (1992) integrates geographical information system (GIS) with a database management system to solve such problems; however, it has limitations: for indoor construction factories, the signal of GIS is sometimes unreliable and the number of facilities that this method can locate is limited. Osman et al. (2003) develop an automated computer system able to minimize transportation costs.

2.1.1.2 Safety and health issues of layout planning

The construction industry's poor safety and health performance can be confirmed by health and safety statistics recorded by related associations. It should be known that many injuries and fatalities are not reported, hence the available statistics are only the tip of the iceberg (Anumba & Bishop, 1997). Fatality levels in the American construction industry exceed 2,000 workers annually; this means the incidence rate is 34 fatalities per 100,000 construction workers (Hinze & Appelgate, 1991).

There are many reasons responsible for accidents on construction sites such as falling objects, tripping over objects at ground level, unsafe site conditions, and improper monitoring of site activities. It has been argued that some causes of construction site accidents can be eliminated and controlled by applying better site layout planning. Other agents, such as negative weather conditions, are nearly independent of site conditions; however, it is also possible to reduce their effects through improvements of site layout planning (Anumba & Bishop, 1997). Reports show that many construction site accidents can be avoided if safety and health issues are considered adequately during the planning of site layout. The planning of site layout provides an opportunity for managers to solve safety issues in the early stage (construction planning phase of the construction process) (Anumba & Bishop, 1997).

For almost all methods developed for site layout planning in previous research, safety, health, and environmental aspects have not yet been thoroughly studied. Specifically, the physical information of environment is not measured properly and cannot be measured timely. Therefore, there is a need to develop a new approach which has the ability to provide these inputs such as the geometric values of construction workplaces.

2.1.2 Human Motion-caused Issues

2.1.2.1 Background of motion study

Motion study is the study that analyzes the influence of jobsite conditions on human motion and also analyzes the detail of human movement, which can then be utilized for ergonomic analysis aiming to assess the health and safety of labour personnel (Golabchi et al., 2016; Guo et al., 2016). In order to solve motion problems in the construction industry, various approaches have been developed in previous research to assess risk factors related to work-related musculoskeletal disorders (WMSDs) (Li & Buckle, 1999). Figure 2-2 shows a typical posture (i.e., bending forward) on construction sites.

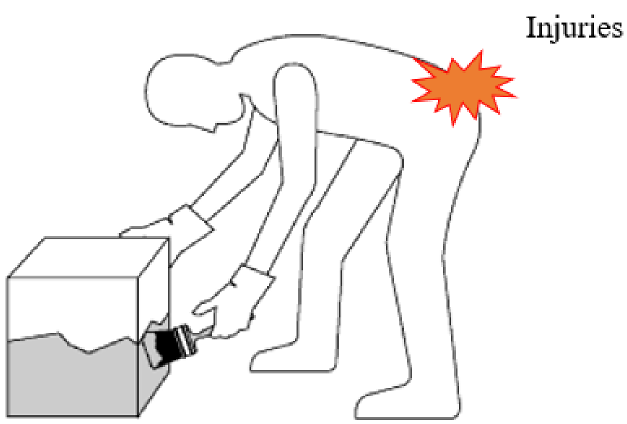

Figure 2-2: Posture of bending forward.

The National Institute for Occupational Safety and Health (NIOSH, 2014) employs the method that a job analyst identifies hazardous actions by observing working postures and movements in real time or from a recorded video. Existing methods focus on how to analyze and monitor ongoing tasks in order to prevent WMSDs. However, the method that can offer information for motion study at the planning stage remains insufficient. In other words, it is necessary to develop an approach to building a given work environment and then eliminating unsafe and unhealthy motions and postures.

Important inputs for motion study are the worker trajectories and the geometry information of workplaces, which are key to conducting motion study of manual tasks. However, continually moving workers and rapid changes in working environments necessitate a significant amount of time and effort to measure the walking distances and physical surroundings because traditional approaches to obtaining geometry information entail time-consuming on-site investigation (Golabchi et al., 2015). Several motion capture methods have been developed to serve motion study. For example, Davison et al. (2001), Chen et al. (2005), and Han et al. (2013) apply computer vision techniques to capture motions from recorded videos. Vlasic et al. (2007) apply mechanical systems (e.g., Meta Motion's Gypsy) to measure joint angles.

This study proposes a quicker and more accurate approach to obtaining both worker trajectories and geometric information of workplaces, which are utilized as inputs for motion study, followed by establishing a platform for analysis and improvement of worker safety and health.

2.1.2.2 Safety and health issues of worker motions

The other safety and health issue that frequently occurs in the construction industry is caused by unsafe human motion. Based on the statistics from the United States Occupational Safety and Health Administration (OSHA, 2007), it is reported that 35%

of construction workers think that they are working in an environment with health risks (Aires et al., 2010). The construction industry continues to have such a high motion-caused injury rate and negative reputation over recent years because construction workplaces have many potential hazards which result in workers performing unsafe motions to do manual tasks (Golabchi et al., 2016).

2.1.3 Machine-caused Issues

Equipment operation is the main task on construction sites. The successful operation of equipment is based on both the equipment and the operator, with more responsibility resting on the operator. However, in the construction workplaces which are continually changing, there are many blind spots and obstacles. Currently, the location information of these blind spots and obstacles cannot be updated to operators frequently, limiting the operator's field of view, depth perception, and also reaction speed (Kim et al., 2006), thus the existence of blind spots and obstacles are the major reason that contact collisions between equipment and ground workers occur (Hinze & Teizer, 2011; Ray & Teizer, 2012). Much research has been carried out to solve this problem. Table 2-1 (Marks & Teizer, 2013; Ruff, 2001; NIOSH, 2007; Teizer et al., 2007) shows the existing technology used for solving the safety problem of equipment operation.

Table 2-1: Comparison of different technology used in existing studies.

Existing technology	Advantages	Disadvantages
GPS	• Low cost. • Work well in outdoor site.	• Unable to perform functionally in indoor sites. • Loss in accuracy when working for short range detection.
Laser	• High accuracy. • High update rate.	• Not able to distinguish ground workers from other objects. • High purchase cost.
Magnetic marking fields	• Able to distinguish ground workers from other objects.	• Requires a system-specific battery for power source.
Sonar	• Low initial investment.	• Susceptible to elements in the construction environment.
Radar	• Supplement the videos recorded on construction sites.	• Not capable of distinguishing ground workers from other objects.

Several previous research studies to prevent contact collision focus on the application of obstacle avoidance theory, which is related to the research on equipment automation (Kim et al., 2006). Considering manual operation is prone to cause more discrepancies, to cause more safety problems, and to be incapable in certain circumstances, observably, computer-assisted equipment operation is more reliable.

To this end, the approach to providing sufficient inputs for computer-assisted automated equipment operation is the research that should be studied. In this thesis, the potential ability that the proposed method can provide sufficient inputs for improvement of equipment operation automation is discussed.

For present literature, Gocho et al. (1992) develop an approach which is able to automatically control wheel loaders by following the wires pre-buried under the ground between loading and dumping points. Similarly, Huang & Bernold (1997) propose a system which is used for dealing with rocks during soil excavation. They equip the backhoe with a load cell; when an obstacle is recognized by the load cell placed between the bucket and the backhoe, the bucket will adjust its posture according to a preset distance, avoiding the crash. Additionally, Lever et al. (1994) adopt fuzzy logic and apply it to a controlling system. By understanding the output of a force-torque sensor equipped on a shovel, the controlling system can then operate the shovel to dig sand. These studies are based on contact between equipment and obstacles, so they can only avoid the obstacle after contact has been made. However, in practice, avoiding the obstacle prior to contact is more key. Therefore, a new approach able to recognize potential obstacles and determine a safe distance to continue operation is needed.

A realistic model for construction equipment operation can be realized by mounting a three-degree freedom manipulator on moving equipment, then through the manipulator's understanding of the surrounding environment can be employed to safely control the equipment. In recent decades, planning the movement of equipment through the understanding of surrounding circumstances is identified as an important problem in robotics (Latombe, 1999). Safe equipment operation can be regarded as finding a collision-free path for a piece of equipment in a congested environment with obstacles (Hussein & Elnagar, 2002). In reality, construction equipment needs to be operated safely in changing environments and complete the assigned tasks without causing any injuries or fatalities.

In recent studies on equipment control, multiple sensors are used to perceive the surrounding circumstances, and then the information obtained is used to execute tasks (Chakravarthy & Ghose, 1998). However, the information and knowledge of environment is approximate; also, sensing is noisy, and the environment is dynamic (Zavlangas et al., 2000). Therefore, most research turns toward the study of real-time detection of obstacles in order to better operate equipment.

Increasing advances in information technology now show new opportunities to better address the current safety problem of equipment control. Obtaining near to real-time geometry information of objects in construction workplaces can help avoid contact collisions between construction equipment and ground workers. Therefore, a new approach that is able to acquire geometry information of objects on construction sites needs to be studied.

To conclude, for site layout planning, motion study, and equipment operation, there is still limited knowledge of an efficient way which can accurately understand the working environment and moving workers. Therefore, considering the advance and the prevalence of computer vision, researchers must turn their focus onto employing computer vision theory to develop a new method.

2.2 Computer Vision-based Reconstruction

In recent years, 3D reconstruction technology has gained its prevalence in building 3D models of workplaces because it saves time and effort for on-site investigation and can produce accurate 3D models. Given that construction equipment works in the dynamic workplace and is affected by surrounding circumstances, the 3D model of workplaces can influence the way that operators control equipment. Also, there are many other applications of 3D reconstruction in previous studies surrounding the construction domain. Therefore, 3D reconstruction has the potential to contribute to this research.

Point cloud data can be processed and analyzed for extracting geometry information of objects (Fathi & Brilakis, 2011). The geometry information obtained from point cloud data can then offer inputs for many applications in the construction industry. For instance, point cloud data: (1) offers higher geometrical accuracy than the traditional modelling approach for time and motion analysis (Golabchi et al., 2015); (2) assists in measuring the 3D shape of the environment for creating as-built BIMs (Tang et al., 2010); (3) enables project managers to identify and correct discrepancies for progress monitoring (Golparvar-Fard et al., 2009); (4) enables 3D status of buildings to be tracked for quality control (Akinci et al., 2006; Bosché, 2010); (5) enables project engineers to model the surface of equipment for equipment operation (Wang & Cho, 2014); and (6) provides an approach to recognizing highway assets (Golparvar-Fard et al., 2012).

Computer vision-based approach has the potential to act as the tool for safety and health monitoring, which can solve the limitations of present manual observational approaches through analyzing useful information from videos (Brilakis et al., 2011; Chi et al., 2009; Golparvar-Fard et al., 2011). Computer vision-based approaches can be categorized into three aspects of risk identification: (1) scene-based, (2) location-based, and (3) action-based (Seo et al., 2015). Specifically, the scene-based approach aims to understand and identify the potential risks in static scenes. For example, it can be regarded as an unsafe scene when predetermined unsafe objects are in the recorded scene. The location-based approach is able to evaluate the risks and hazards by analyzing the geometry information of objects in the construction workplace. For example, when the distance between equipment and workers is too close, there will be potential risks (e.g., contact collision). Also, if the location of equipment is changing too quickly, this means this equipment may travel with excessive speed. Action-based risk identification focuses more on detecting the unsafe action of construction workers (Seo et al., 2015). For instance, construction workers improperly lifting objects with awkward postures can cause injuries (i.e., WMSDs) (Bureau of Labor Statistics, 2012).

Currently, the main methods of producing point cloud data are images based approach, video based approach, and laser scanning based approach. Images based approach to producing point cloud data does not require any extra light energy generated from the digital camera, which means it can work in existing light (Teizer, 2008). The procedure of this approach mainly includes two steps. In the first step, project engineers need to capture images of objects. When the image collection is complete, those images need to be processed. The basic principle of data processing is based on the triangulation relationship of the location of a same point in two different images (Zhu & Brilakis, 2009), which is called the structure-from-motion algorithm. A simple interpretation of structure-from-motion algorithm is shown in Figure 2-3. A key point (A) of an object is presented in two different images (A1 and A2), which are taken from two different viewpoints. The relationship between the locations of this point in two images can be utilized for recovery of the 3D shape of the object. Also, it should be noted that, the greater the number of key points that are captured, the more accurate the 3D shape.

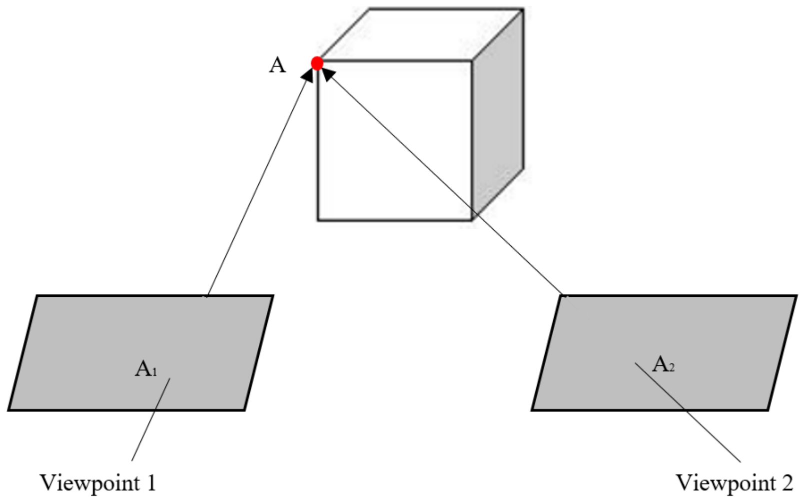

Figure 2-3: Interpretation of structure-from-motion algorithm.

The second approach is video based. This approach can also work in the existing light environment (Teizer, 2008) and requires more than two video frames as input because the later video frame needs to be matched to and built on the previous video frame. Then the sequence of video frames can be used to reconstruct the spatial location of each point of objects. However, the video based approach is still at the early stage (Zhu & Brilakis, 2009) and can easily affect the accuracy of point cloud data when noise exists (Remondino & El-Hakim, 2006).

The third method is using a laser scanner which can produce emitted laser when collecting data. The basic principle of this approach is similar to echolocation. Specifically, when emitted laser meets an object, the object can reflect the laser back to the laser scanner, the duration information of emitting and return is used to build a spatial relationship of elements in a space (Teizer, 2008). One key feature of laser scanning is that it allows for accurate wide-range measurement (Golparvar-Fard et al., 2011; Jaselskis, 2003). However, the main limitation of applying a laser scanner to generate point cloud data is the potential cost (Fathi & Brilakis, 2011).

Stereo videos (or depth images, because stereo videos need to be processed frame by frame, which is the same as multiples of depth images) are videos generated by stereo cameras. The stereo camera has two lenses, both of which can record the video for an object from different views (i.e., usually the distance between two lenses is measured in tens of centimeters). Since the object is captured from different views at the same moment, the disparity map can be easily calculated, and then the point cloud can be rebuilt based on the disparity map.

This study selects stereo camera to collect stereo videos and depth images for the acquisition of worker trajectories and modelling workplaces for the following reasons: (1) advanced or valuable devices are not required to collect data such as laser scanners, but rather, affordable stereo cameras can complete the data collection (the ZED stereo vision camera is employed in this study which costs Can$449.00); and (2) it is more effective to track worker movements by recording videos.

2.3 Summary

2.3.1 Practical Motivation

Numerous statistics show that the accident rate is still high in the construction industry. Although productivity is important for any construction company, safety and health require attention. Otherwise, the injuries will cause significant loss. It has been found that site layout planning, worker motions, and equipment operation are the three main reasons responsible for injuries occurring in the construction industry. More importantly, the factor for improving these three aspects is the same: better understanding the changing working environment and dynamic worker motions. Therefore, the method proposed in this research is studying how to improve the existing approach to capturing the layout of construction workplaces.

2.3.2 Need of Research

The proposed method in this research has the potential to provide sufficient inputs for rebuilding construction workplaces, allowing the managers, engineers, and workers the opportunity to better understand the working environment. To this end, several experiments are carried out to test if the proposed approach is able to address the present safety and health problems in the construction industry.

CHAPTER 3. VISION-BASED TRACKING OF WORKER TRAJECTORIES IN BUILT WORKPLACES

3.1 Overview

An overview of the proposed methodology to address vision-based tracking of worker trajectories in the built environment for safety and health study is shown in Figure 3-1.

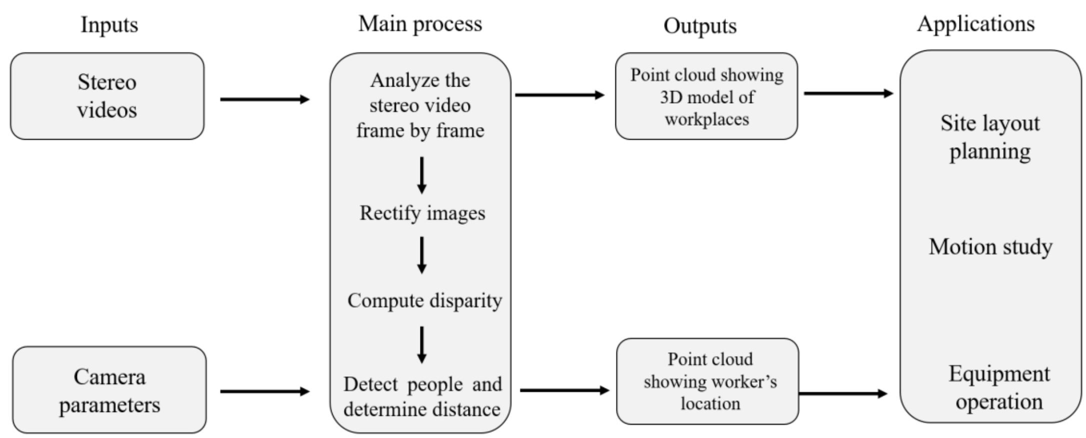

Figure 3-1: Overview of the research approach.

Two types of inputs (i.e., stereo videos and camera parameters) are required and need to be collected first. Next, the collected data is processed through rectifying images, computing disparity, and determining distance; and finally the point cloud data showing workplaces and workers' locations can be reconstructed accurately. Geometry information of workplaces and location of moving workers can be then extracted and used for redesigning the jobsite layout plan, studying human motion, and improving machinery operation.

3.2 Data Preparation

Two types of data are required in this research:

- Stereo videos
- Camera parameters

The stereo videos can be captured by stereo cameras, which have two or more lenses. For stereo cameras, there is a fixed distance between lenses. This allows the camera to record the scene from different views at the same time, therefore giving it the ability to build the third dimension. In this research, a stereo camera is used for collecting these two types of data.

3.2.1 Camera Parameters

Camera parameters are important for creating 3D environments and determining workers' locations because camera parameters describe the position and orientation of the right camera relative to the left camera, which will be later used in the stereo system to rebuild accurate point cloud data. In order to obtain the camera parameters and transform it to the format that can be used later, the following steps should be carried out (Figure 3-2).

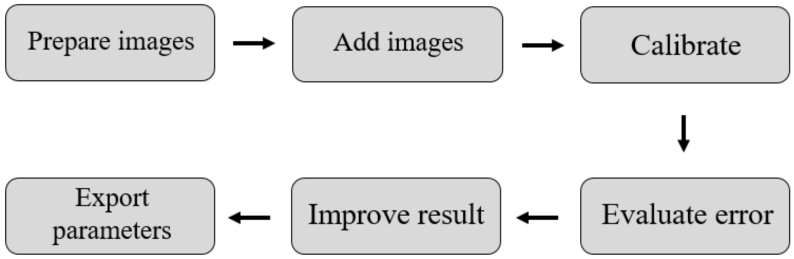

Figure 3-2: Process of obtaining camera parameters.

Theoretically, camera calibration involves finding the internal camera qualities that affect the imaging process. Specifically, the image center, focal length, scaling factors for row pixels and column pixels, skew factor, and lens distortion can all be determined through camera calibration (Camera Calibration, 2013).

- Prepare images

  A checkerboard was used as a target when capturing side-by-side images. Each side of the square is 23 mm (Figure 3-3), which is a required and important input for calibration. A total of 25 image pairs are taken to obtain the best result. Figure 3-4 shows one of 25 image pairs. As can be seen, the scene is stored from different views at the same moment.

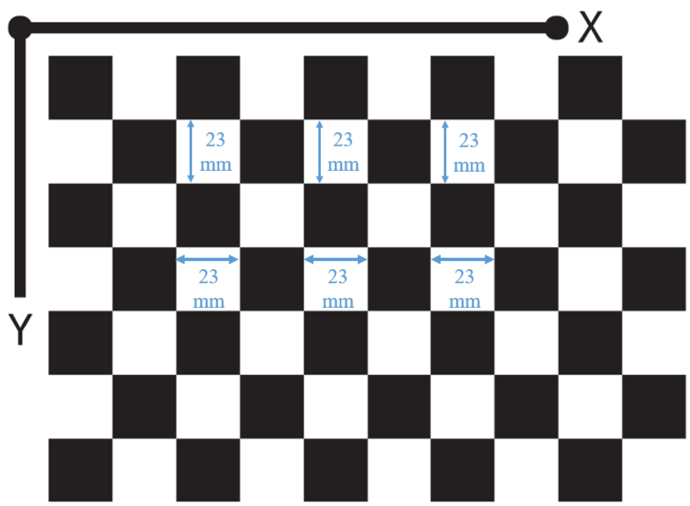

Figure 3-3: Size of checkerboard.

Figure 3-4: Capture side-by-side images for checkerboard.

- Add images

  An application named Stereo Camera Calibrator is selected for obtaining camera parameters because of its convenience for users.

- Calibration

  After loading all image pairs, the calibration step can be initiated. Figure 3-5 shows the calibration result. The code embedded in the Stereo Camera Calibration application can automatically detect points of intersection (center of green circle), checkerboard origin (center of yellow square) and re-projected points (center of red cross).

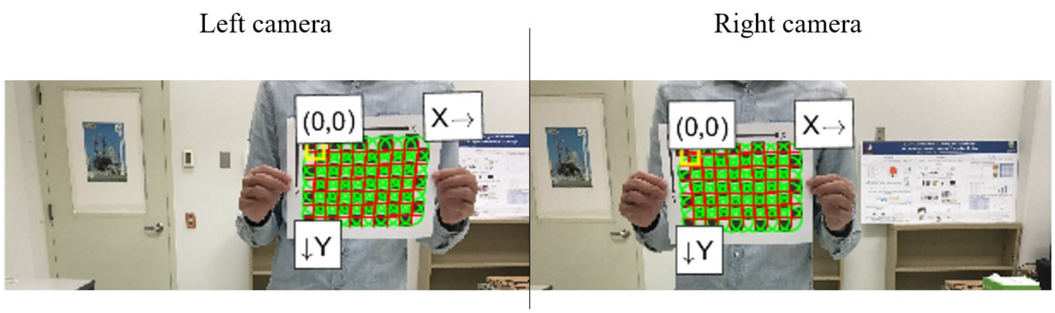

Figure 3-5: Calibrated checkerboard.

- Evaluate error

  Errors should be evaluated and minimized in order to reconstruct clear point cloud data and in order to accurately calculate the distance. Two methods are available to evaluate the result. Examining re-projection errors is the first method. Re-projection error is a geometric error which depicts the image distance between a projected point and a measured one. This error is used to evaluate how closely and accurately an estimate of a 3D point recreates the point's true projection (Hartley & Zisserman, 2003). The other method is checking extrinsics of the camera (i.e., the location of the camera and the location of the checkerboard).

- Improve

  For re-projection errors, the pairs with an error greater than 1 should be removed to decrease overall error to be less than 1. Extrinsics of the camera provides a camera-centric view of the patterns; users can also check if the relative position of two cameras is correct. Figure 3-6 shows an example of re-projection errors.

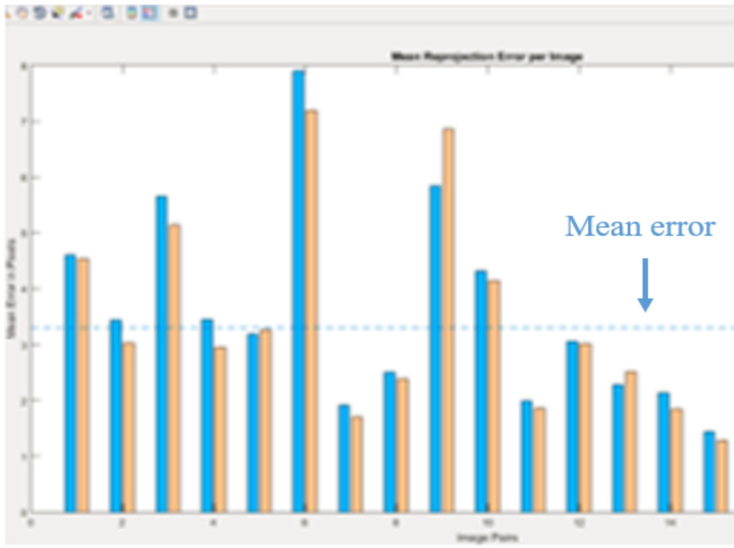

Figure 3-6: Re-projection errors.

- Export

  Once the result meets a certain requirement, it can then be exported as a MAT file for future use. This file contains information such as the intrinsic and extrinsic parameters of the camera, and the distortion coefficients.

3.2.2 Introduction of Instrument

After making comparisons among different potential devices, ZED stereo camera (Figure 3-7) is selected based on affordability and compatibility with available computers. This camera is capable of taking side by side images and recording stereo videos, which are the features required for this study. Table 3-1 (www.stereolabs.com) shows important specifications of this camera.

Figure 3-7: ZED stereo camera.

Table 3-1: Technical specifications of stereo camera.

Technical specification	Value
Dimensions	175 × 30 × 33 mm
Weight	159 g
Depth range	0.7 − 20 m
Stereo baseline	120 mm
Working condition	Indoors or outdoors

This camera is suitable for data collection due to its portability (i.e., small size and light weight). Also, the depth range is sufficient for the current research as experiments are conducted in a fabrication plant.

3.3 Workplaces Reconstruction and Trajectories Acquisition

In this section, the detail of the proposed method is explained. The proposed method employs the depth estimation approach to rebuild the point cloud data for changing workplaces and moving workers. Depth estimation refers to those algorithms which aim to obtain and acquire the representation of spatial structure of an object (i.e., measure of the distance among points of the observed scene).

In computer vision, there are several approaches related to depth estimation. Basically, these methods can be categorized into two types: active approaches and passive approaches. Specifically, active methods require putting energy in the scene. The most commonly used energy to measure the distance is light. Then the system can recognize the scene by analyzing the reflected light. However, in reality, the data collection is often conducted on construction sites. Extra light energy may influence the normal working environment. Therefore, the approach which does not require any extra effect is more valuable, known as passive approaches. These approaches can be carried out with natural light and optical information from a captured scene. Then, through a computational method, the spatial structure of the recorded scene can be reconstructed (Sanz et al., 2012). Therefore, the passive method is employed in this research.

The stereo video used to compute the depth can be collected in different ways. The widely used method involves two cameras or lenses, closely placed, which point to the scene to capture the data (as shown in Figure 3-8). Theoretically, the scene is projected into the image plane, and in each pixel only one point can be projected; therefore, the depth information is naturally erased during the projecting (Sanz et al., 2012). Then, computational methods are needed to mathematically retrieve the depth information from the video frame (i.e., left video frame and right video frame).

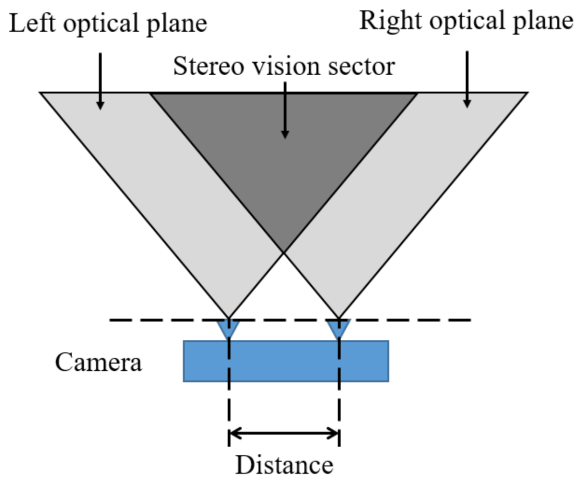

Figure 3-8: ZED stereo camera.

The prepared value of camera parameters is analyzed first because it shows the relative location and orientation of two lenses of the stereo camera (D) and also shows the depth range (R-R') (Figure 3-9). D is a fixed distance value, and R-R' describes the depth range only in which the depth perception of objects is accurate.

The other input is the stereo video data. The left and right videos are displayed as a group, which means each left video frame matches each corresponding right video frame. Therefore, the view of an object is shown from two different locations.

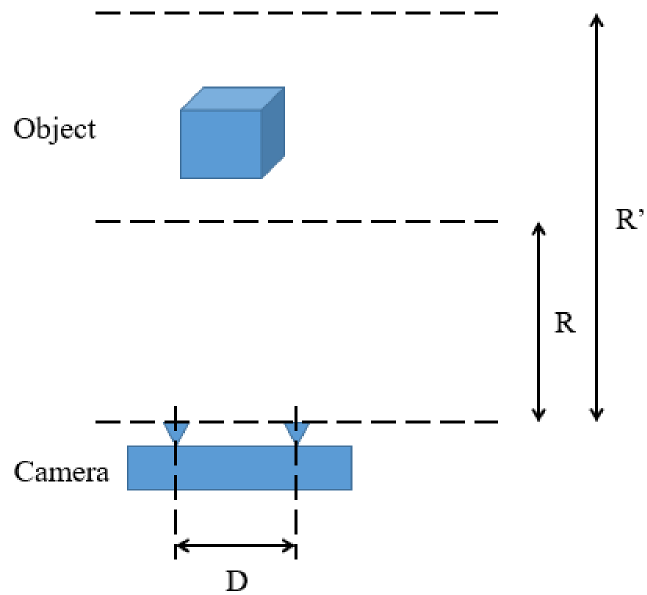

Figure 3-9: Parameters of the stereo camera.

Rectifying video frames matches the location of a point in left view to the location of the same point in right view, which leads to the left location of the point and the right location of the point being rectified to be located on the same pixel row.

Before the step of rectification, the same point in two corresponding video frames (i.e., two corresponding images) should be matched first. This offers the platform where the distance of same point can be removed later. The commonly used method of detecting the feature in different images is the Scale Invariant Feature Transform (SIFT) descriptor (Lowe, 2004). Figure 3-10 below describes how SIFT works for feature detection.

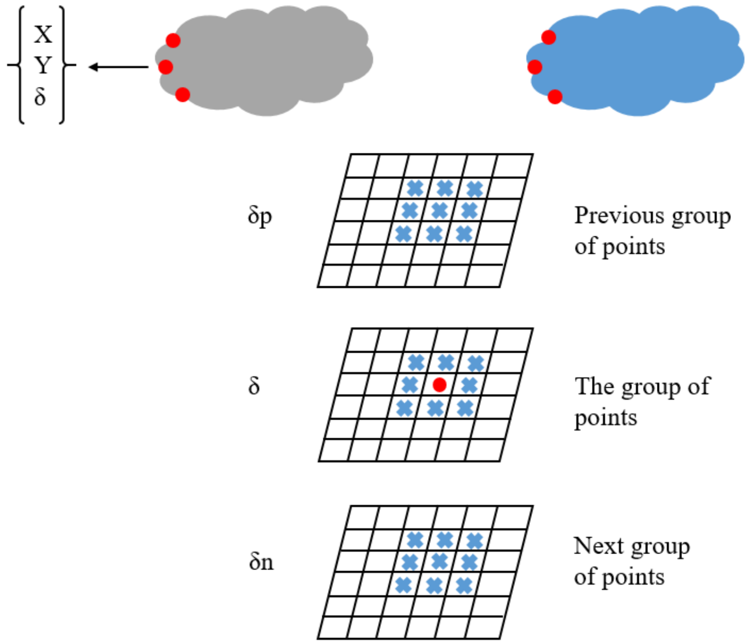

Figure 3-10: Theory of SIFT.

In this figure, the grey cloud represents the scene captured in the left view and the blue cloud represents the scene captured in the right view. The red point represents the potential key points. Each image is assigned same size grid to provide the value on x and y axis. Therefore, every point represented by pixel will have a distinct (x, y). Since the alignment of two lenses is not perfect. Therefore, every two corresponding images will have slightly different scale (i.e., δ). Then, SIFT can employ (x, y, δ) to locate the point, which means there is a key point at (x, y) at δ scale. When the (x, y, δ) of each point is confirmed, each pixel (i.e., a point) will be compared with its 8 neighbor pixels, and also compared with 9 pixels in the previous scale and 9 pixels in the next scale

(Lowe, 2004), by means of which, the feature can be matched in two corresponding images.

When the feature is detected. Then the two locations of same feature are rectified to the same row, which means now they are at the same horizontal height. Figure 3-11 shows this relationship. In the original video frames, the scene of point A is captured from two different angles of view (i.e., left view and right view). The projections of point A in these two views are A1 and A2. In the original frames, the heights of A, A1, and A2 are different (i.e., they are not in same pixel row). Therefore, the epipolar plane (i.e., the plane containing A, A1, and A2) is not horizontal. This will cause difficulties when computing the disparity. Therefore, the rectified distance is moved; then, the epipolar plane becomes horizontal. In other words, the 3D plane (as the plane containing A, A1′, and A2′) now can be regarded as a 2D line, which can help in calculating the disparity.

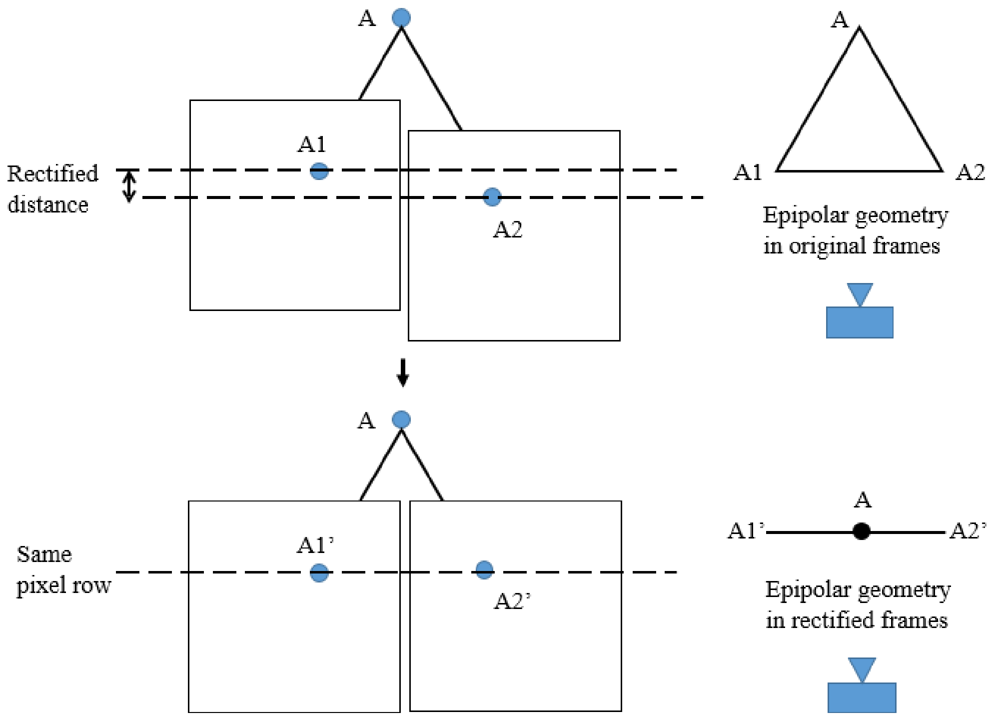

Figure 3-11: Rectification of video frames.

Figure 3-12 shows the epipolar line in left and right images. A given point detected in one image (i.e., left image) must also be found in the corresponding epipolar line in the other image (i.e., right image).

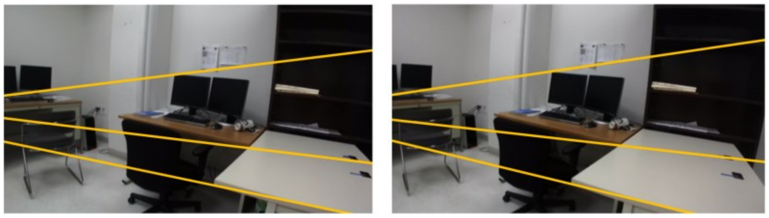

Figure 3-12: Epipolar lines in two different perspectives.

The rectified stereo video can then be used for computing disparity where the distance of each pixel between left frame (or left depth image) and right frame (or right depth image) can be calculated. As the video frames are already rectified, one dimension is eliminated. In this case, if we have a point A1 = (x1, y1) in one image, the corresponding point A2 = (x2, y2) in the other image is at the same height as A1 (i.e., height 1 = height 2). Then, the disparity is defined as:

$$\text{Disparity} = (x2 - x1, y2 - y1)$$

The depth information of the point cloud can be obtained from the disparity map because its depth is proportional to the corresponding disparity.

After rectification, the epipolar lines become horizontal as shown in Figure 3-13.

Figure 3-13: Corresponding points in two images.

Based on the disparity map and proportional relationship, the point cloud can be rebuilt. Figure 3-14 shows this relationship. DL represents the fixed distance between two lenses of the stereo vison camera. D represents the disparity, which is known from the result above. Proportionally comparing this with the result in the first step, the depth information (R) can be calculated and obtained, and then the spatial structure can be used to reconstruct the point cloud data.

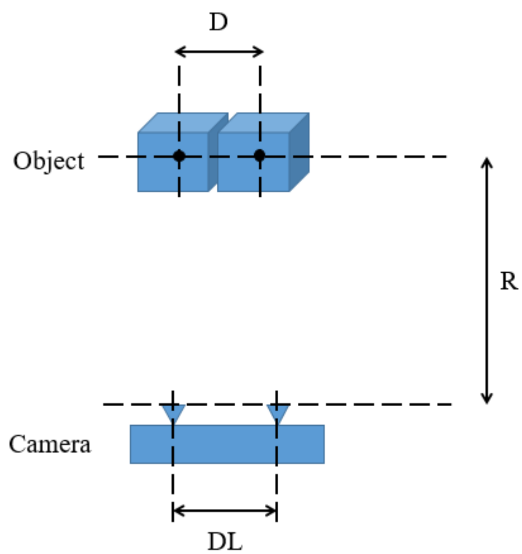

Figure 3-14: Depth perception.

Tracking of moving objects is an important task in the study of computer visualization. One application is that the tracking of human trajectories can be used for motion study to improve the performance of safety and health in the construction industry. Unlike the image-based 3D reconstruction, stereo video-based 3D reconstruction is able to capture dynamic scenes. Specifically, capturing images around a static environment is achievable and then the collected image can be processed and used for rebuilding the 3D models of the environment. However, when it comes to dynamic scenes, for example, capturing images around a moving construction worker is not achievable. Also, since the same scene cannot be captured from different viewpoints (i.e., workers are moving), the point cloud data of trajectories cannot be reconstructed. Stereo video-based 3D reconstruction offers a method to record the moving object, and only requires having the left and right images for a scene at a specific time. The depth information can then be calculated and extracted from the stereo video frame. In this way, the point cloud data of a scene (explained above) can be updated from time to time; therefore, the point cloud data of the moving object can be consistently rebuilt and then the trajectories can be obtained from the geometric information of the point cloud data.

3.4 Discussion of the Stereo Vision System

In the above discussed stereo vision system, the stereo vision camera is employed, which has two lenses closely placed. In other words, the distance between the two lenses is short. Also the distance cannot be changed to accommodate the need of different objects. However, compared to the real depth that needs to be measured, the distance between two lenses is relatively short. Given that the depth perception is reconstructed basically based on the triangulation relationship, the short distance between two lenses can lead to inaccuracy. Figure 3-15 shows the improvement that could happen when the two regular cameras are placed as on set on the same horizontal height.

As it can be seen in Figure 3-15: (1) The stereo vison camera has the fixed and short distance between two lenses (i.e., 0.12 meters), which leads to the depth range is 0.7 - 20 meters. Therefore, this stereo vison system can only work well for objects that locates no more than 20 meters to the location of stereo vison camera. When it comes to the objects which are located at a longer distance (i.e., more than 20 meters). The depth perception will become more and more inaccurate along the distance between the object and the camera becomes longer. (2) When two regular cameras are employed, the distance between two cameras can be changed longer to satisfy the need of observing bigger objects and objects that are at far distance, because the depth perception (i.e., depth range) is longer.

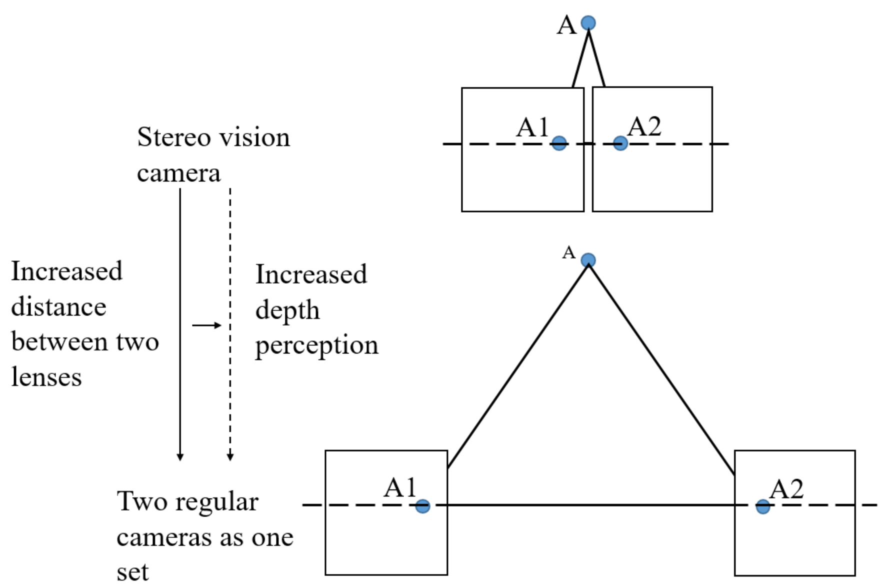

Figure 3-15: Increased depth perception based on increased distance.

3.5 Summary

Point cloud data of the workplace contains rich geometry information and point cloud data of the worker's location and plots the worker's trajectories. Traditionally, these kinds of information take much more time and effort to obtain, which leads to insufficient understanding, thereby resulting in a high accident rate. By employing the proposed method, the above mentioned information can be easily obtained, and can be the input for the purpose of carrying out the tasks outlined below and discussed in detail in the implementation section.

- Provide a real 3D model of the working environment (known dimensions of physical environment) for planners to evaluate potential hazards and risks on construction jobsites.
- Provide worker trajectories for analysis of manual tasks.
- Better design workplace layouts, improve human motion, and control equipment.

CHAPTER 4. EXPERIMENT OF RECONSTRUCTING MODELS AND TRACKING TRAJECTORIES

4.1 Accuracy Evaluation of Environment Reconstruction

Based on the literature review, it can be seen that providing sufficient physical information about construction workplaces and workers is of great importance for site layout planning, motion study, and equipment operation. Therefore, the accuracy of the physical value (e.g., geometry information and visualization of objects) should be ensured. In this section, the proposed method (3D reconstruction based on stereo video) and also Structure from Motion algorithm are tested to demonstrate why the proposed method is the superior method for health and safety studies.

4.1.1 Description of Experiment Target

3D reconstruction based on stereo video is a method for reconstructing environments. In order to guarantee the accuracy of implementation, experiments should first be conducted to test whether or not the proposed method can meet certain requirements. An experiment is conducted in the lab, in which the rebuilt target is a 40 m^2 room. In the room, 11 tables are arranged around the wall, simulating a real workplace (i.e., workstations along the wall of a workplace). The capability of the employed method to detect the correct shape of objects in an environment can thus be tested. In this study, a 120-second video is recorded by the stereo vision camera. In this video, all objects are included and shown in the video to help reconstruct every detail of the room.

4.1.2 Result

The result of the experiment is shown in Figure 4-1. It can be seen that the result is still reliable even when the scene is reconstructed from the inside. All objects are clearly rebuilt. When the point cloud is open in a 3D coordinate system, the distance of each object can be easily obtained, which can be later used in reorganizing the layout of the jobsite.

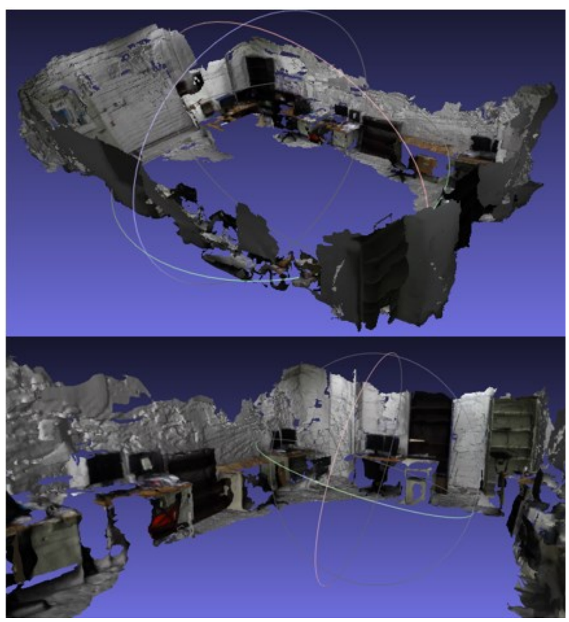

Figure 4-1: Reconstructed point cloud of the room.

Figure 4-2 is the point cloud of the selected room open in a 3D coordinate system. The *x*-axis and *y*-axis depict the horizontal level, and the *z*-axis shows the height of the house. Based on the 3D coordinates, geometric information of the environment can be extracted more accurately and quickly than with the traditional method (i.e., on-site measurement by investigators).

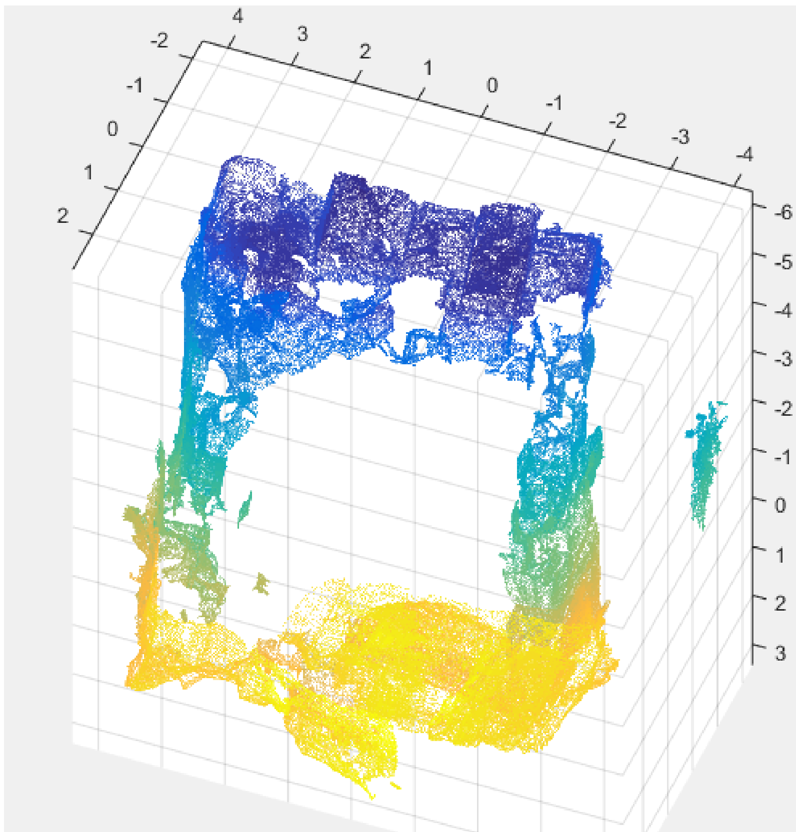

Figure 4-2: Reconstructed point cloud of the lab.

4.1.3 Comparison with Structure from Motion Algorithm

The structure from motion algorithm is a basic theory in 3D reconstruction, that has been employed in many previous studies. Researchers have also employed this algorithm to reconstruct point clouds. The result of this method is discussed here to demonstrate why the stereo video-based method is adopted rather than using the structure from motion algorithm.

The selected target (Figure 4-3) is a house whose shape is a regular cube with a triangular prism as the roof. Around the house, there is no obstacle hindering the path for collecting data, which is the main reason why this house is selected. In addition, several white-frame windows are distinguishable from the red walls. This is a feature that needs to be tested in order to determine if the proposed method is able to recognize small objects in a given environment.

Figure 4-3: Selected target house.

In this research, VisualSFM (Wu et al., 2011) is selected to generate point cloud data, which is achieved in four steps: importing images, matching images, computing 3D reconstruction, and computing dense reconstruction (Falkingham, 2013). 230 images are captured around the object.

After data processing, the point cloud of the house is successfully reconstructed as shown in Figure 4-4. As can be seen, the shape is accurately rebuilt (i.e., cube body with triangular-prism roof). Also, the white-frame windows are all clearly shown in the point cloud, which shows that the method employed in this research has the ability to recognize small objects in an environment.

Figure 4-4: Point cloud of the house.

As can be seen in the figure, some parts are missing in the point cloud; for example, the top side of the roof is not rebuilt at all (circle 1), and some walls above the front door are missing (circle 2 and circle 3). This is because the data is collected from the ground view, and the view of the camera has limits. If the data were to be collected from 360 degrees around the selected house, based on the available results it can be predicted that all parts of the house could be accurately rebuilt.

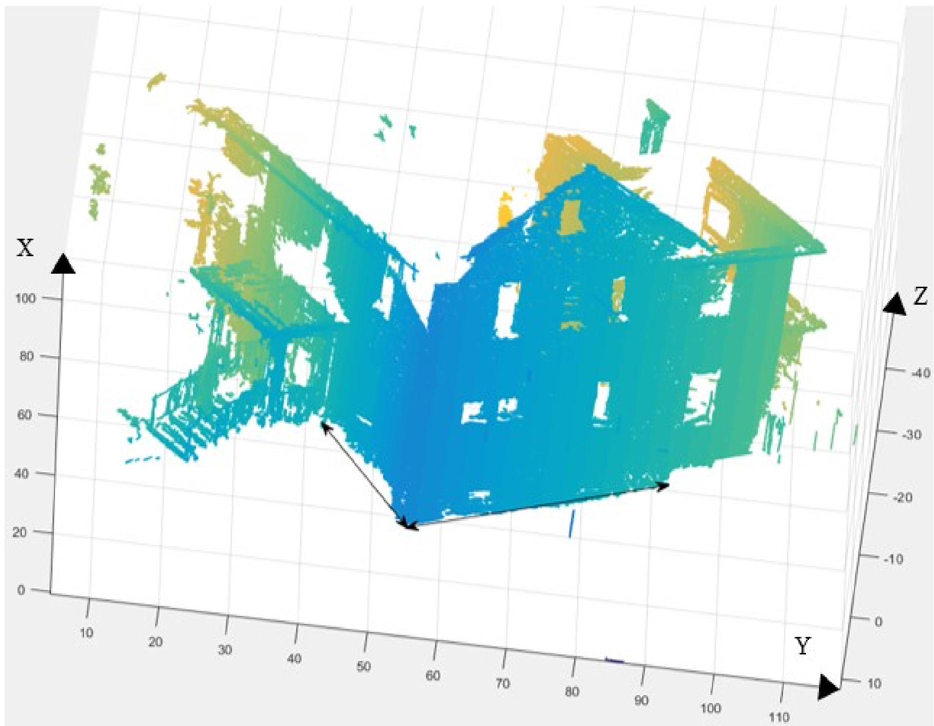

Figure 4-5: Reconstructed point cloud of the house.

Figure 4-5 is the point cloud of the selected house open in a 3D coordinate system, wherein the dimensions of the house can be accessed.

The durations of each processing step are listed in Table 4-1, where the computation time may vary depending on the configuration of the computer. The computer used in this research has a 3.40 GHz processor and 16.0 GB of installed memory (i.e., RAM).

The total computation time for 3D modelling of this steel welding workplace is found to be 412 minutes.

Table 4-1. Time spent for each step.

Step	Time (minutes)
Images collection	30
Import images	2
Match images	160
Compute 3D reconstruction	20
Compute dense reconstruction	200
Total	412

Considering that work environments in construction frequently change and the duration of rebuilding such a small house requires around 7 hours, it can be expected that for large construction sites it will take considerably longer, and therefore it is not feasible to obtain sufficient understanding of workplaces through this method. More importantly, the structure from motion algorithm only works for still scenes (i.e., pictures taken for an object from many different views). Therefore, it lacks the ability to record worker trajectories.

4.2 Accuracy Evaluation of Trajectories Acquisition

Based on the literature review, it can be seen that a worker's motions in performing manual tasks have the potential to cause WMSDs. In this context, worker trajectory can be a useful tool for motion study. The potential risks and hazards can then be eliminated through motion analysis.

4.2.1 Description of Experiment Target

The approach to acquiring human trajectories is also tested before implementation, with the experiment carried out in a lab environment. Three scenarios are considered and tested in the lab in order to closely simulate a real workplace. In real jobsites, it is noted, workers can move to anywhere through any route. Figure 4-6 shows the location of the stereo camera and the worker's moving direction. The following three scenarios encompass the basics of any possible route. Additionally, the same walking speed is used in the experiments to check how the employed method works for real construction workers.

- Scenario 1: The location of the stereo camera is fixed at the south side of the lab. A person moves 150 cm from north to south.
- Scenario 2: The location of the stereo camera is fixed at the south side of the lab. A person moves 150 cm from east to west.
- Scenario 3: The location of the stereo camera is fixed at the south side of the lab. A person moves 150 cm from northeast to southwest.

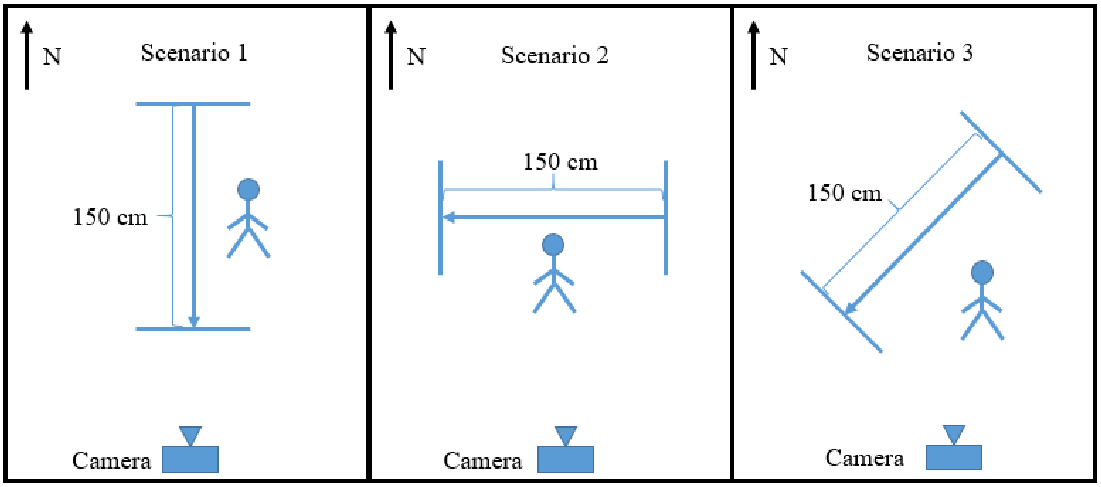

Figure 4-6: Three different scenarios.

The real lab experiment is shown in Figure 4-7. Some tables are arranged in the scene to simulate workstations in a workplace. Also the distance between the location of the stereo camera and the location of the scene is similar to the distance between the available location for the stereo camera and the locations of working areas; by doing so, the camera range can also be tested to check if it would be sufficient for real projects.

For each scenario, a 10-second video is recorded by the stereo vision camera. 10 seconds allow the research (as the worker) to walk from the start point to the end point. This can simulate the real task in construction jobsites. For example, a welder walks 5 m to pick up welding materials.

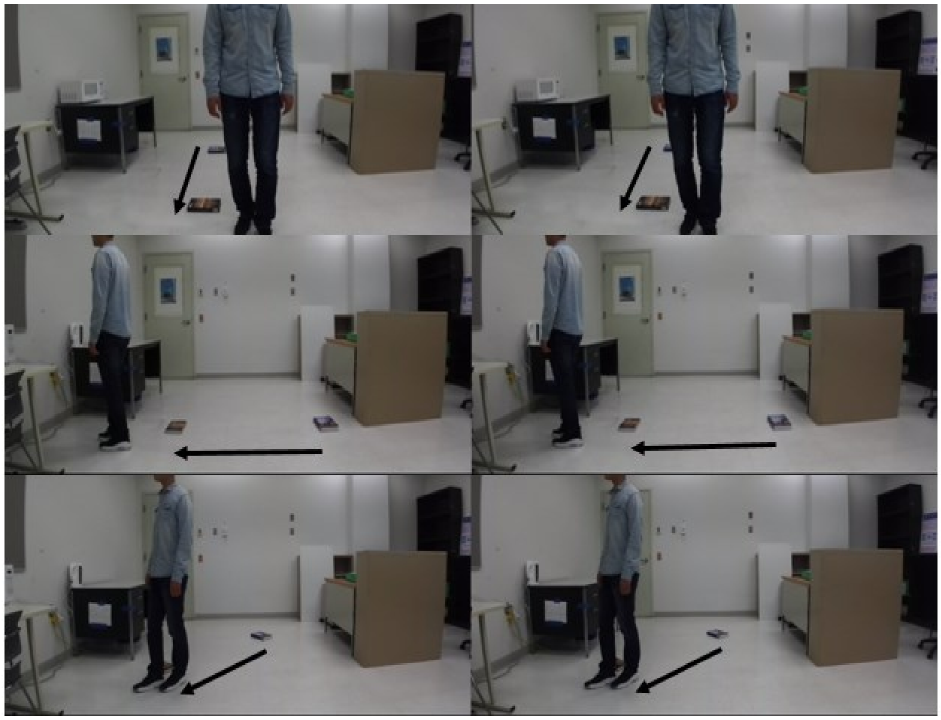

Figure 4-7: Three different real scenarios.

4.2.2 Results

The collected data is processed using the proposed method as described below. First, the disparity map is built (Figure 4-8). Motion trajectories are then calculated and reconstructed from the disparity result as shown in Figure 4-9. The above mentioned three scenarios are shown from top to bottom.

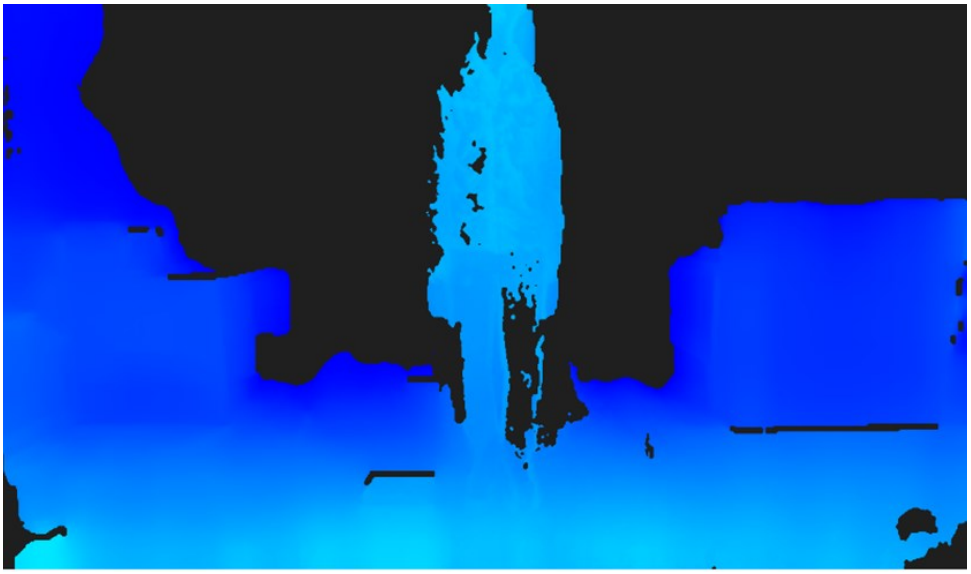

Figure 4-8: Disparity result.

In the left side of Figure 4-9, it can be seen that both the moving person and the background objects are correctly rebuilt, and the trajectories are recorded consistently. In the right side of the Figure 4-9, the point cloud of trajectories is opened in a 3D coordinate system. Based on the *x*-, *y*- and *z*-axes, the moving distance can be easily extracted.

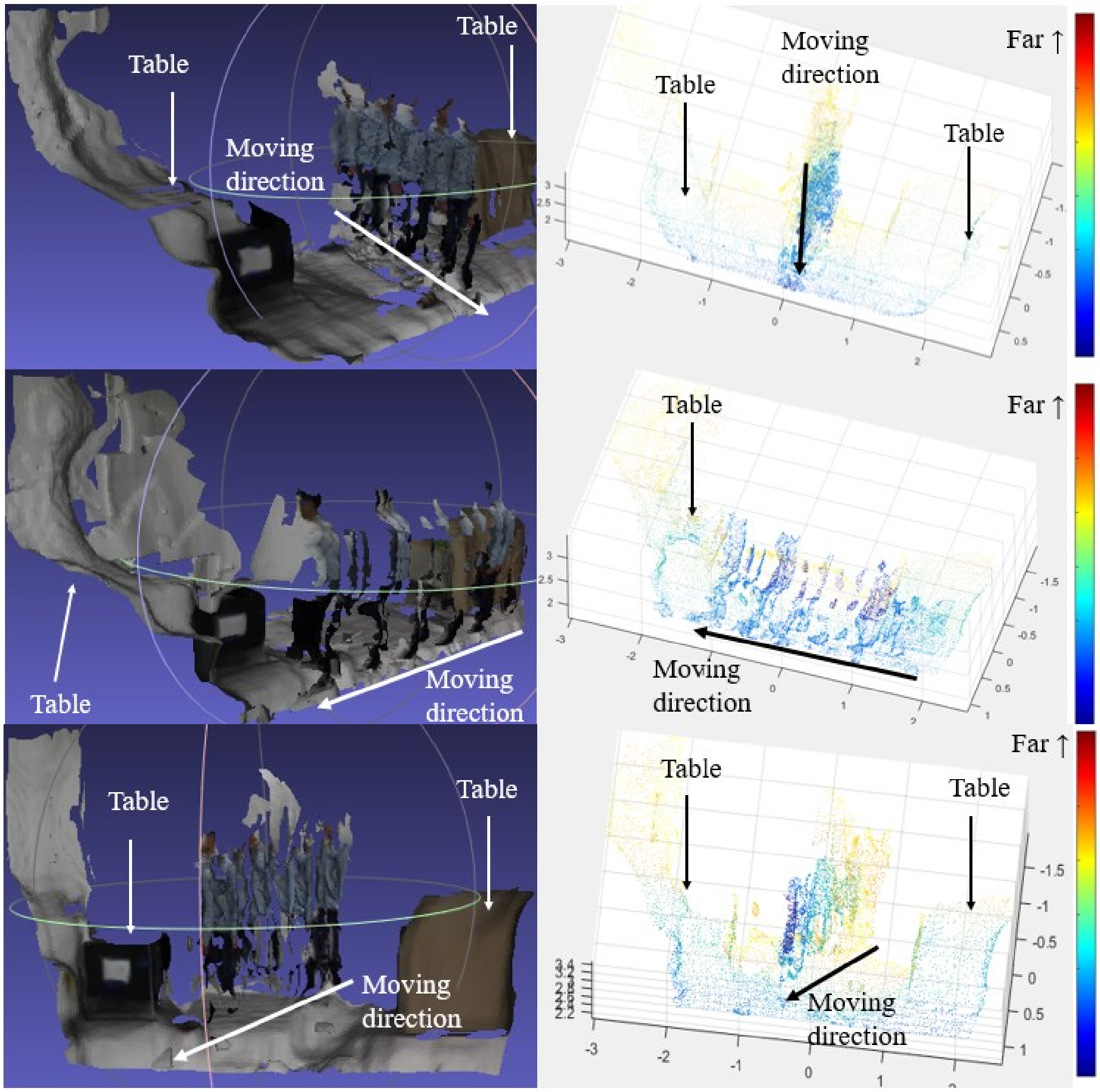

Figure 4-9: Point cloud of trajectories (scenario 1 to 3 is from top to bottom).

In addition, for the point cloud data in 3D coordinates, the colour of human trajectories changes from red to blue, which means that the depth of each location is changing as well. Red denotes the furthest side while blue denotes the closest side. The coloured bar located at the right side of the figure shows this change. It should be mentioned that, for scenario 2, the color of the point cloud stays the same because there is no depth change throughout the motion. This also confirms that the employed method can effectively detect the depth change (i.e., movements) in the real world.

Table 4-2: Acquisition of moving distance.

Scenario								
1			2			3		
NO.	Distance (cm)	Error (cm)	NO.	Distance (cm)	Error (cm)	NO.	Distance (cm)	Error (cm)
1	139	-11	1	142	-8	1	159	+9
2	141	-9	2	147	-3	2	159	+9
3	157	+7	3	158	+8	3	142	-8
4	157	+7	4	147	-3	4	148	-2
5	146	-4	5	148	-2	5	142	-8
6	138	-12	6	151	+1	6	139	-11
7	158	+8	7	152	+2	7	142	-8
8	154	+4	8	157	+7	8	157	+7
9	159	+9	9	159	+9	9	156	+6
10	158	+8	10	154	+4	10	154	+4
Error range	[-12, 9]		Error range	[-8, 9]		Error range	[-11, 9]	
Ratio (%)	[-8%, 6%]		Ratio (%)	[-5%, 6%]		Ratio (%)	[-7%, 6%]	
Note: The measured distance is 150 cm. Unit is centimeter.								

The distance between the start walking location and the end walking location of the point cloud of trajectories is measured first (i.e., the measured distance equals to 150 cm) in order to evaluate the accuracy of the proposed method. Table 4-2 above describes the findings.

Ten sets of experiment are conducted for each scenario. Next, the estimated distance (i.e., the distance that calculated by the proposed method) is listed in the table. The error between the measured one and the estimated one is then calculated. Instead of using mean error, the error range is used here to describe the accuracy performance, because mean error cannot show the maximum error that cloud occur, which is important for tracking of trajectories.

1) Error range: [A, B]. It shows the interval in which the error value could be.

- Error A which is a negative value means that the estimated distance is less than the measured one A centimeters.

$$A = -\left| \text{Measured Distance} - \text{Estimated Distance} \right|$$

- Error B which is a positive value means that the estimated distance is more than the measured one B centimeters.

$$A = \left| \text{Measured Distance} - \text{Estimated Distance} \right|$$

2) Ratio (%): [C, D]. It uses the interval of ratio to make the error more explicit for analysts.

$$C = A \,/\, \text{Measured Distance}$$

$$D = B \,/\, \text{Measured Distance}$$

Based on the result, it can be seen that the error range of the second scenario has the shortest interval of error range while the first scenario has the longest interval of error range. According to the theory underlying the proposed method, one reason can be that if the distance change is directly facing the camera, the camera can lose some accuracy because what the camera sees is that a person is slowly moving in the environment. However, if a walking person's motion is not straight toward the camera, the camera can recognize the motion by comparing the environment blocked by the person. Therefore, in this case, the proposed method can perform much better.

CHAPTER 5. DISCUSSION ON CONCEPTUAL APPLICATIONS

In this chapter, potential applications of the rebuilt workplace models and worker trajectories are discussed. Based on the geometric information of workplaces (e.g., dimensions of objects) extracted from the point cloud data, it is possible to effectively understand the changing working environment in construction sites. Then potential obstacles on construction sites can be identified at the planning stage by, for example, analyzing the safety zones. Also, the obtained information can provide a frame of reference (e.g., available space to move equipment) when planning routes for equipment operation.

5.1 Background of Case Study

In this chapter, the proposed method is implemented in a field setting. First, data (videos and images) are collected. Then, the point clouds of workplaces and of moving workers are rebuilt. Finally, potential applications in human motion study, layout design, and equipment operation are discussed.

The case study company is a steel fabrication company which for more than 40 years has been a leading construction company in Canada. The reason a fabrication company is selected for the case study is that steel fabrication plays an important role in steel construction projects, including design, procurement, steel fabrication, delivery and on-site erection (Azimi et al., 2011). Steel fabrication involves changing raw steel into the exact configuration needed for a structural frame, which take places in fabrication shops where many construction workers are working with large moving equipment in congested areas. It provides a suitable venue to test the performance of the proposed method. A general fabrication process consists of cutting, detailing, fitting, welding, painting (optional), and loading. The fabrication shop is usually divided into many small workplaces such as fitting workplaces, welding places, etc. Figure 5-1 shows the locations of different workplaces in the fabrication shop.

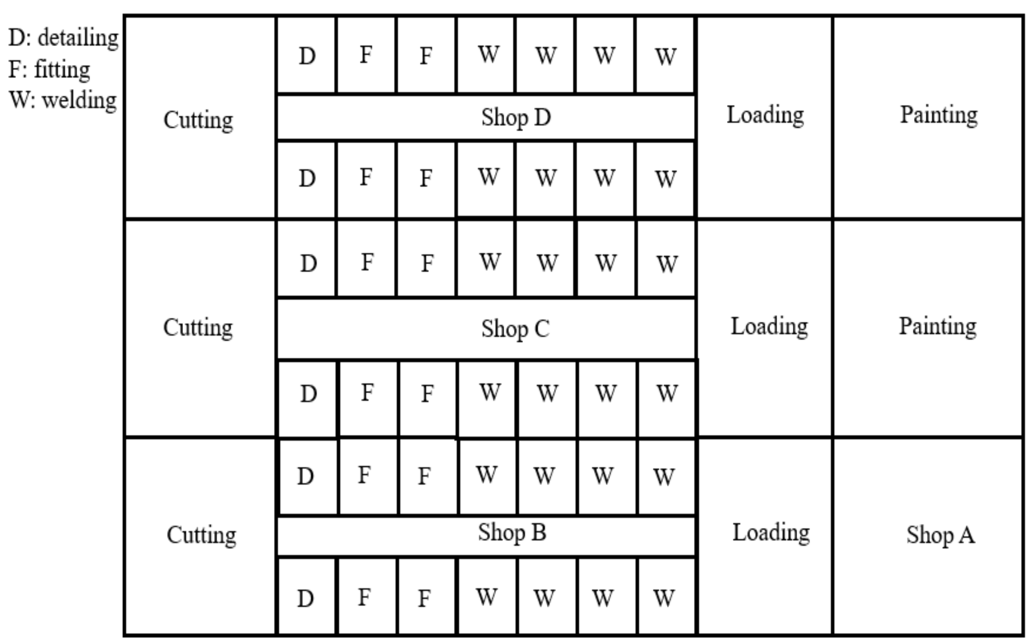

Figure 5-1: Simplified view plan of the fabrication shop.

Each workplace is equipped with specialized equipment to support skilled workers according to the required functions. Figure 5-2 shows an example of the welding workplace. In this workplace, the workstation is located in the middle area, and equipment is set up around one side of the jobsite.

Figure 5-2: An example of the welding workplace.

The manager is responsible for properly determining the workload of manual tasks and planning facility locations (especially for temporary facilities) in order to ensure worker health and safety and also to maintain the production rate. The proposed method can then serve as the tool to provide information for carrying out such analysis at the planning stage.

5.2 Reconstruction of Workplaces and Acquisition of Worker Trajectories

The selected area is a welding workplace in steel fabrication shop D. This area is surrounded by boards, providing a relatively small space. For wider spaces, a high depth perception ability to rebuild an accurate point cloud of the workplace is required; otherwise, the point cloud cannot meet the accuracy requirements for the safety and health analysis. The selected workplace is equipped with a workstation and hand-held tools. The point cloud is shown in Figure 5-3, where the blue shading shows the available moving space for workers and the grey shading shows the location of a workstation.

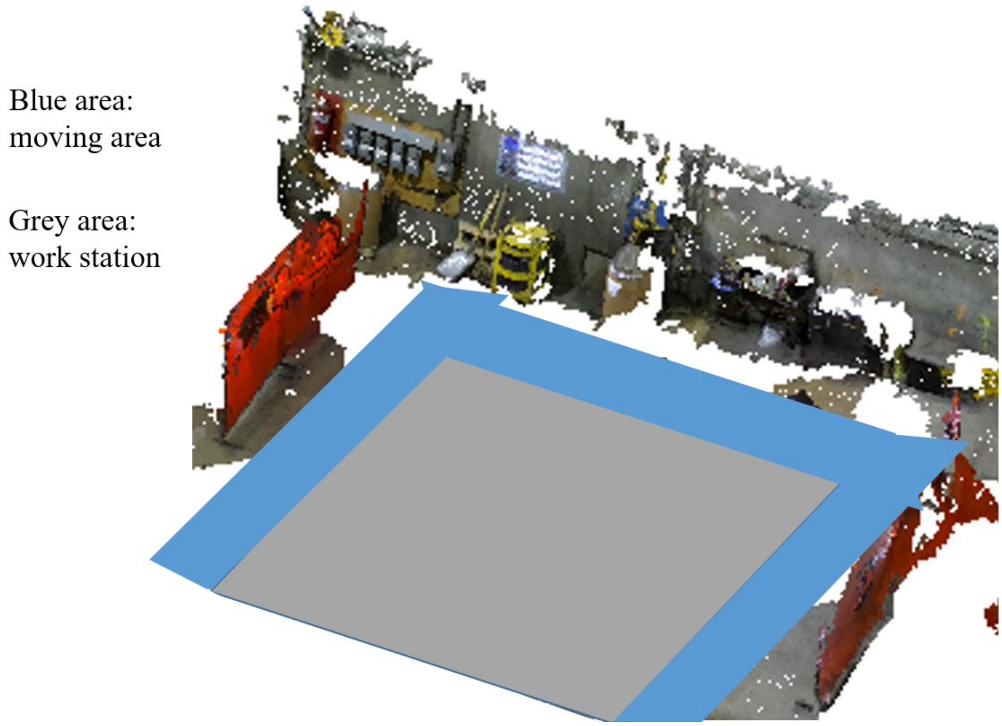

Figure 5-3: One of welding workplaces.

Additionally, the welder's movements in the workplace are simulated. These movements are recorded as stereo videos in order to track trajectories. Figure 5-4 shows three moments of worker movements.

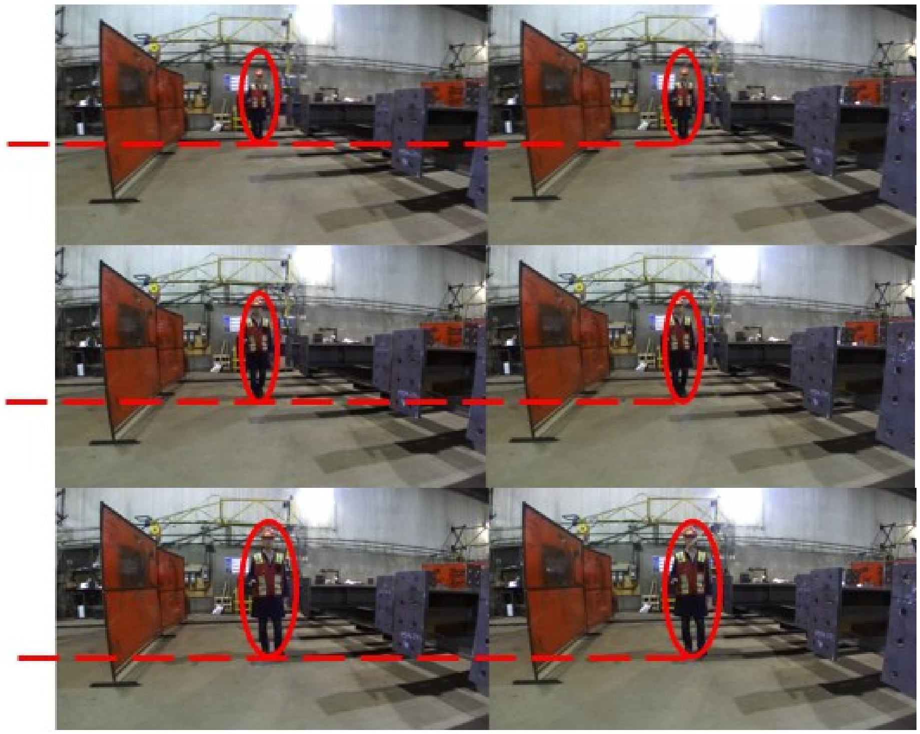

Figure 5-4: Three moments of worker movement.

Based on the result calculated in the experiment as described in a previous chapter, the proposed method is shown to have the ability to track worker trajectories in the fabrication shop, which can be analyzed for improvement of safety and health.

5.3 Human Motion Analysis

[1]In construction, worker safety and health often garners less attention than productivity improvement. As such, the injury rate continues to be high. To address this problem, ergonomic analysis is increasingly being applied in the construction industry.

[1] This section is partly based on the work of: Guo, X., Golabchi, A., Han, S. and Kanerva, J. (2016). 3D Modeling of Workplaces for Time and Motion Study of Construction Labors. 16th International Conference on Computing in Civil and Building Engineering (ICCCBE), Osaka, Japan, July 6-8, 2016.

Ergonomic analysis minimizes the risk of injury by taking ergonomics into account in workplace design. Time and motion study of construction labour can significantly contribute to ergonomic analysis. The workplace point cloud and worker trajectories obtained from the proposed method can provide geometric information (e.g., dimensions of objects and workers' actions in performing manual tasks) and visual information (e.g., visualization of up-to-date construction jobsites), which can be used for identifying unhealthy worker actions and unsafe jobsite layouts, which can then be mitigated.

Predetermined motion time systems (PMTSs) are employed in the construction industry to determine the amount of time required to perform a given manual task (Farrell, 1993). Many researchers have studied manual activities in order to develop accurate PMTS. Some of the most widely used PMTSs are (1) Methods-Time Measurement (MTM) (Maynard et al., 1948), (2) Modular Arrangement of Predetermined Time Standards (MODAPTS) (Heyde, 1966), and (3) Maynard Operation Sequence Technique (MOST) (Zandin, 2002). MODAPTS is selected as the tool for the present study because this system uses easy-to-understand human terms (Aft, 2000; Golabchi et al., 2015). MODAPTS functions as follows: Manual tasks performed by workers, referred to herein as "human motion" can be represented by multiple movement units. Each unit equals a single finger movement (0.129 seconds). Two kinds of input (i.e., measurable input and visual input) are required in order to calculate the duration of manual tasks in MODAPTS. Regarding the measurable type of input, geometry data such as the dimensions of an object or worker moving distance can be obtained based on the worker trajectories. For the visual type of input, it can be acquired by checking the locations of objects in the reconstructed point cloud of the workplace. For instance, the pick-up and placement locations of the object can be used to determine the complexity of grasping an object. Therefore, this method saves significant time when obtaining these two types of data. On-site investigation and checking of numerous notes are thus no longer required. Table 5-1 (Guo et al., 2016; Golabchi et al., 2015) describes the approach to obtaining the data. Based on this table, a value can be assigned to each input, and the duration of performing manual tasks can then be obtained. Based on this, ergonomic analysis can be conducted and safety and health of construction workers can be improved.

Table 5-1. Approach to obtaining inputs for MODAPTS.

Class	Description	Required input	Options	Method
Movement (M)	Workers move hands.	Distance that hand moves.	-	Measure distance between start and end points.
Get (G)	Workers grasp objects.	Complexity of picking up the object.	Simple pick up Difficult pick up	Visually check the workplace conditions.
Put (P)	Workers place objects.	Complexity of placing an object.	General location Scheduled location Precise location	Visually check the workplace conditions.
Walk (W)	Workers walk.	Distance that a worker walks.	-	Measure the distance between start and end points.
Load (L)	Consider weight of object.	Weight of the object that workers handle.	-	From records and notes.

As a case study, the reconstructed point cloud of the welding workplace and the worker trajectories are used. In this case, a worker moves their hands a distance of 70 cm to pick up with a simple grasp a steel plate that weighs 5 kg, then carries the plate 4 m, and moves their hands 60 cm to place the plate at a precise location. Table 5-2 lists the values for this case, as published in (Guo et al., 2016). A simplified explanation of how to determine the value for each class can be found in Appendix A.

Table 5-2. Values for each class

Class	Property	Value assigned
Start movement (M)	70 cm	7
End movement (M)	60 cm	6
Get (G)	(Simple)	1
Put (P)	(Precise)	5
Walk (W)	4 m	31
Load (L)	5 kg	1

This example is expressed in MODAPTS code as M7G1L1W31M6P5, and the sum of the values of each class is represented by total MOD, which is 51 in this example. Therefore, the total duration of this example task is 51 × 0.129 = 6.579 seconds. Once the durations of manual tasks are obtained, with checking the workplace point cloud and worker movements, ergonomic analysts are able to check the amount of time during which a worker maintains an uncomfortable posture. If this uncomfortable posture has to be repeated several times a day, and the total amount of time exceeds a risk limit, then this posture is identified as likely to contribute to musculoskeletal injury. Ergonomists should thus take action to reduce the time that a worker maintains uncomfortable posture, thus the safety and health of workers can be significantly improved.

Considering the prevalence of 3ds Max or other similar software in the construction industry, the obtained worker trajectories and the point cloud of a workplace can also be used to precisely remodel manual tasks. The traditional approach to observing manual tasks requires on-site investigation. Even when using a camera to record what happens in the construction site, there are still blind spots, and it is probable that these represent locations where the risk of worker injury exists.

The point cloud data is a set of points in a 3D coordinate system, and these points represent the external surface of an object. Therefore, it contains rich geometry information. Once the point cloud data is generated, this point cloud data can be processed through several steps such as format conversion, scale setting, etc. Then, an identically sized workplace can be built in software such as 3ds Max or Autodesk Revit. The point cloud of each object can also be moved or modified in the point cloud of the environment.

It is also noted that a considerable amount of research has been conducted on the extraction of the human skeleton from video recordings of human movement. Such skeleton models can be used for motion analysis where the worker's trajectories can contribute. Worker trajectory information is obtained from the proposed method. If the trajectory value is assigned to the human skeleton, then the skeleton can perform the manual tasks, as in the real world, in the rebuilt environment in software such as 3ds Max. By viewing the animation in the software, construction planners are able to observe worker motions as they would occur in the real construction site. Potential risks can then be identified and proper actions can be taken to address the risks found. This potential application is shown in Figure 5-5. Traditionally, the construction planner needs to view the video in order to understand how workers perform manual tasks, but sometimes the existing objects in the jobsite can block the planner's view. As a result, it becomes difficult to identify if there is sufficient space to safely perform a specific task. With the help of worker trajectories, the entire working motion can be simulated in the 3D space, which offers the opportunity for construction planners to check the work from every view. Then, for example, any potential collision between the worker and existing objects can be eliminated.

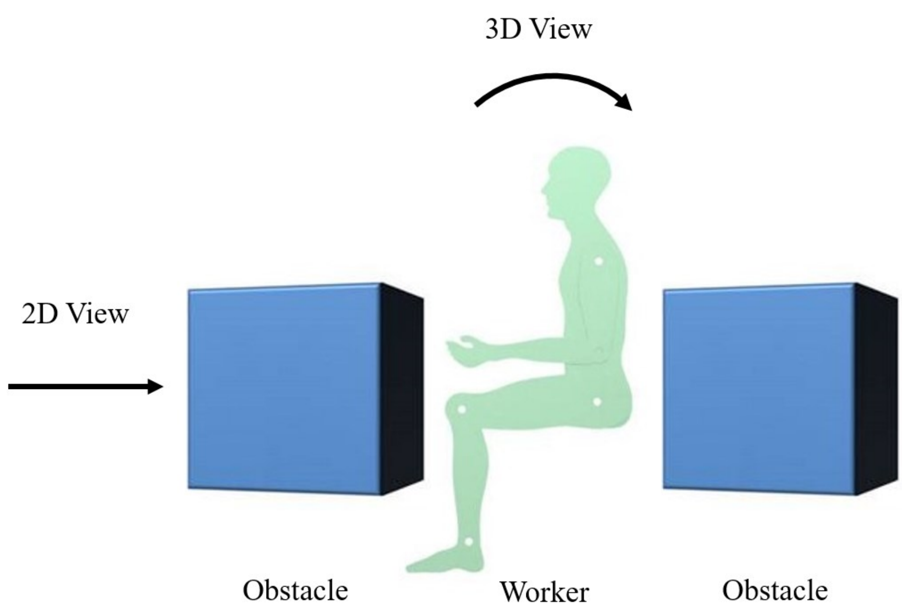

Figure 5-5: Animation remodelling the construction work.

5.4 Layout Reorganization

Site layout design include two aspects: (1) layout design of temporary facilities and (2) layout design of permanent facilities. The temporary facility for the case study company (steel fabrication company) is a disposal bin for leftover steel. The permanent facilities are workstations and machine (e.g., cutting machine).

Disposal bins are important in fabrication shops because they provide a place to store leftover steel. The leftover steel is usually of a large size, such that randomly discarding the leftover steel will cause problems for the on-site transportation. The disposal bin is usually placed on the one side of the road to support fabrication tasks in the fabrication shop. However, the road is not only used to place disposal bins; the more important function of the road in fabrication shops is to provide space for transportation. In the fabrication shop, cranes are used to transfer the processed steel from a given workplace (i.e., cutting, fitting, welding, loading, etc.) to the subsequent workplace. The large crane carrying a significant amount of processed steel also needs to access the road which is used to place the disposal bin in order to transfer product. Therefore, reasonable placement of the disposal bin can potentially prevent collisions among the disposal bins, processed steel, and cranes. Additionally, in some cases permanent facilities (i.e., workstation) also need to be slightly relocated in order to ensure sufficient space for different fabrication projects. Considering the size and weight of the workstation, pre-simulation of the workstation adjustment is required. Therefore, the point cloud data of the workplace offers a means to design the layout of the disposal bin and to simulate the relocation of the workstation. For example, the point cloud of a workplace can be divided into two parts: (1) the point cloud of the workplace without the workstation and (2) the point cloud of the workstation. Then, the location of these two point clouds can be moved and adjusted until a suitable plan is found. Figure 5-6 shows the point cloud data for this case.

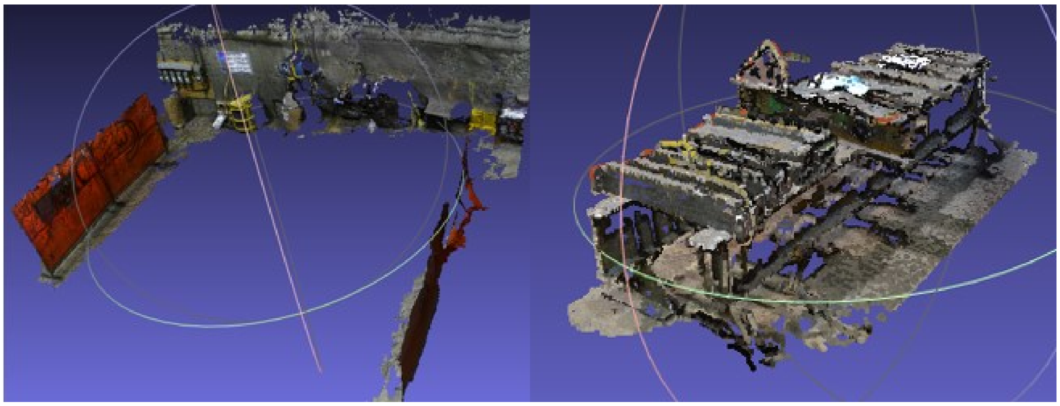

Figure 5-6: Point cloud of workplace without workstation and point cloud of workstation.

5.5 Equipment Operation

The main equipment operation problem in the case study company pertains to crane operation. In the fabrication shop, cranes are frequently used for transferring processed steel from one workplace to the subsequent workplace. For example, the crane operator uses a crane to pick up the welded steel to the loading area and then loads the fabricated steel to the truck. Next, trucks can transfer the fabricated steel to construction sites. Workplace layouts differ depending on the project and its associated space requirements. The shape of fabricated steel also varies depending on the project specifications. Therefore, there are potentially blind spots and newly created obstacles in the fabrication shop, which are likely to cause collisions.

3D modelling of workplaces is an essential part of equipment operation. Constructing a correct and complete workplace model offers a platform where efficient and effective equipment operation can be studied (Barry et al., 1995). The approach of real time modelling has to be not only fast but also capable of dealing with uncertainty and changes in construction sites (Kim et al., 2006). Sparse point cloud achieves the efficiency of acquisition of the depth data (Kwon et al., 2004). Traditional approaches such as CAD-based systems are precise but slow, and are therefore not suitable for solving operational problems.

This study develops a system which can be used for safety improvement of manual equipment operation by analyzing the information obtained from the 3D model of a workplace. The detailed processes are described as follows.

By analyzing the information obtained from 3D models of the workplace, the processes of manual equipment operation are established for the purpose of understanding the basic principles of equipment operation in construction sites. Before equipment operation, the first step is to use the stereo camera to record stereo video or to capture depth images in order to model the workplaces, since the 3D model of the construction site can serve as a visual tool and can provide sufficient geometry information of the workplace for path analysis. Once the 3D spatial modelling is complete, the operator will analyze the point cloud data in the computer to identify potential blind spots and obstacles in the construction jobsites. Next, the equipment operator will design an optimized path to allow the equipment to complete its tasks while avoiding any collisions.

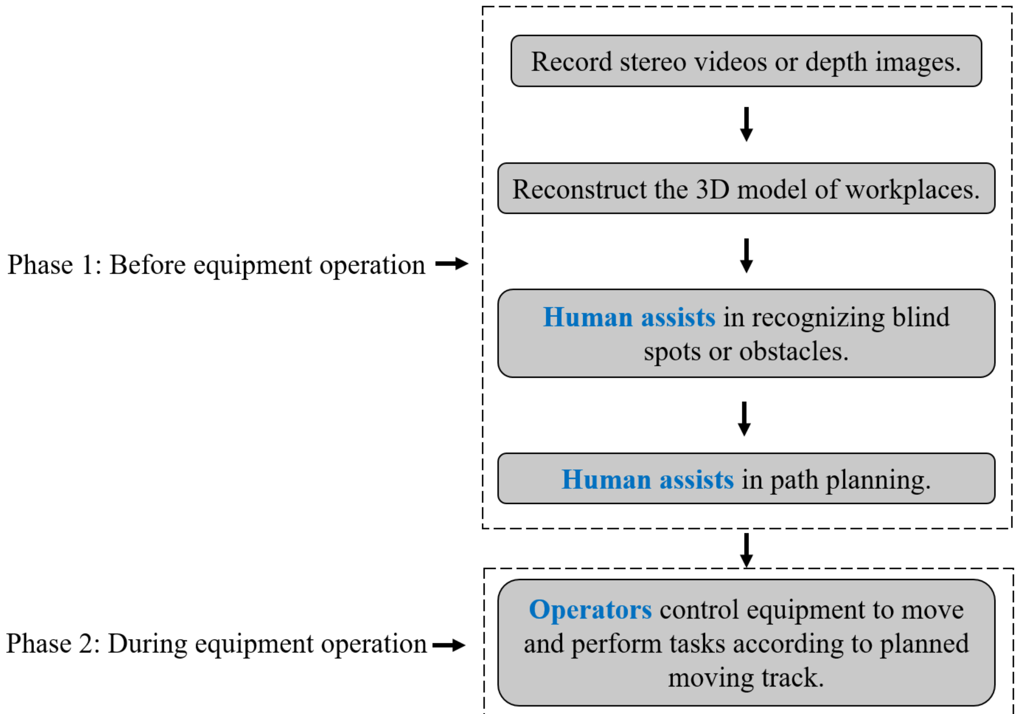

Figure 5-7: Processes of manual equipment operation.

The point cloud of the workplace offers a platform where the overall workplace layouts can be sufficiently understood at the planning stage. Since the drawings of fabricated steel (dimensions of fabricated steel) are always known, the model that simulates how to move the fabricated steel can be animated in the built environment. Planners are also able to optimize the road resources to facilitate the use of limited transportation space. More importantly, the blind spots and obstacles in the fabrication shop can be identified in the planning stage by analyzing the point cloud of the workplace. A reasonable transferring route can be planned, by means of which the operator's field of can be expanded, and the reaction speed depth perception can be improved.

Moreover, in contrast to the traditional approach (i.e., construction equipment is controlled directly by human operators), the point cloud data with rich geometry information can be combined with information technology. The use of a computer-assisted system should also be taken into account as it can potentially perform well when sufficient inputs are available, given that the required input is physical information about the environment and the point cloud data is able to offer such information. The error-prone nature of human operation can thereby be eliminated.

CHAPTER 6. CONLUSION

6.1 General Conclusion

The accident and injury rate in the construction industry has remained high in recent decades. According to numerous statistics collected by the Association of Occupational Health and Safety, it can be seen that motion-caused injuries, site layout-caused accidents, and equipment collision-caused accidents are the three main risks within the construction work environment.

This research has explored an approach employing stereo video-based 3D reconstruction, and then demonstrated that the rebuilt point cloud of the workplace and obtained worker trajectories can (1) provides a more time-efficient way to build 3D models of frequently changing workplaces, given that the traditional approach requires engineers to carry out on-site investigation; (2) offers a way to accurately record worker trajectories. This obtained information can then be utilized to improve (1) motion study (e.g., time and motion study) by providing reliable inputs such as moving distance value and action value, (2) site layout design by providing the exact dimension of objects in jobsites and (3) equipment operation by expanding operator's field of view.

6.2 Research Contributions

The contributions of this research can be summarized as follows:

- Academic contribution: The research has explored an approach employing stereo video-based 3D reconstruction theory to percept the depth information of real objects, and then to reconstruct the environment and to track the trajectories of workers. To this end, the theoretical method of using stereo vison camera to generate geometry and visual information is systematically studied, and then the experiment results and the discussion of application indicate the reliability of the proposed approach for safety and health analysis.
- Practical implications: The method proposed in this research offers a new way to understand actual jobsites. Traditionally, planners can only get access to drawings, notes, contracts, pictures and videos to understand the manual tasks performed by workers in construction sites. With this research, real workplaces and even worker movements can all be remodeled in the computer, which provides a 3D world where planners can have better understanding of actual working conditions. Additionally, the proposed method, different from existing motion capture methods, offers a new way to understand the human motion. Better plans can then be prepared to improve the safety and health of construction workers through site layout planning, motion planning, and equipment operation.

6.3 Research Limitations and Future Work

The experimental results and implementation show that the proposed method can be used to achieve the objective of acquiring worker's trajectories and obtaining geometry information. The following list describes limitations and recommendations for future research.

- The stereo vison system used in this research employs the stereo vision camera to collect data. Theoretically, the triangulation relationship can work well for the depth perception in any cases. However, the distance between two lenses is fixed and relatively short, compared to the size of real objects. Therefore, in reality, the method used in this research will have less accuracy when reconstructing large objects and objects that are at far distance. One potential approach to solving this problem is using two regular cameras as one set. In other words, two regular cameras can be placed at the same horizontal height to play the role of a stereo vison camera. Since the distance between two cameras can be made longer, the depth perception will improve. This approach will be tested in the future work.
- Tacking of moving workers not only include tracking the moving distance, but also include tracking the moving angle. Considering the distance and angle together can better design human motion in order to improve safety and health performance. The angle analysis of point cloud data will be further studied.

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