PHOTO-MODELING FOR CONSTRUCTION SITE SPACE PLANNING

A Thesis

Presented to

the Faculty of the Department of Construction Management
University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Construction Management

By

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December, 2011

PHOTO-MODELING FOR CONSTRUCTION SITE SPACE PLANNING

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ACKNOWLEDGEMENTS

I want to sincerely thank my advisor and thesis advisor Dr. Linggugang Song for his tremendous support during my thesis dissertation. He gave me the right direction and always encouraged me equally during the time of failures and success. I also want to express my sincerest gratitude to Dr. Neil Eldin for his gracious support and feedback. His motivation for the perfection will always inspire me in my future career. Here, I want to mention names of my boss D J Krchnak, Professors Robert Burrow and Donna Kacmar for helping me throughout my thesis and sharing professional experiences.

This second Master's is only possible because of the support I received from my family and my roommates Mahesh and Abhijit who are my real inspirations. I want to dedicate this thesis especially to my mother who cared so much for me during my second Master's study.

ABSTRACT

Space planning of complex and congested construction sites affects construction safety and field performance. The traditional method of relying on visual inspection and 2 dimensional (2D) drawings for layout planning is limited by the fact that construction sites are usually highly complex and dynamic. Existing site conditions must be frequently captured to represent its latest status for space planning. Recent development of 3 dimensional (3D) reality-capturing technologies, such as laser scanning and photo-based modeling, allows an accurate measurement of a job site and its representation in a 3D format. This research proposes a photo-modeling approach as a faster and cheaper alternative to 3D laser scanning for capturing as-built conditions for space planning purposes. This technique automates the reality-capturing process in which series of overlapping 2D photos are used to derive as-built 3D model of a construction site. The feasibility and effectiveness of the proposed approach is demonstrated in an industrial case study.

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CHAPTER 1: INTRODUCTION

1.1 Background

Construction site conditions are dynamic in nature, involving numerous activities and resources scattered on a construction site. Thus, it is important to understand the site layout or planning in details for the overall execution of a construction project. There are different views related to space planning. Site planning can be the art of arrangement of structures on the land and shaping in between spaces. It tries to locate objects and activities in space and time (Lynch and Hack 1984). Another concept defines site layout as an optimization problem. Construction site layout is considered as the design problem of arranging a set of pre-determined facilities on a set of pre-determined sites in order to optimize and satisfy a set of layout constraints (Cheng, 1995). For example, optimization of distances is required in order to determine the location of permanent and temporary facilities and the movement of heavy equipment.

Today's complex and congested construction sites pose issues related to safety and field performance. Thus, it is important to understand the impact of poor site or space planning on construction activities and overall project performance. Safety risk and low productivity can usually be attributed to inefficient space planning and poor site logistics (Tawfik and Fernando, 2001). Space planning has been heavily researched, especially space constraints which lead to safety and productivity issues on a construction site (Akinci et al., 2002; Tawfik and Fernando, 2001). Many studies discussed space planning as an embedded task within construction planning and scheduling. Riley and Sanvido (1997) mentioned the importance of the sequencing of various activities, their identification and potential spatial conflict resolution for efficient space planning. They also emphasized a greater need for preventing interference between crews, equipment, and stored materials. Tawfik and Fernando (2001) suggested that 20% of reported construction accidents can be attributed to poor site logistics. Accidents occurred due to falling objects or collision of vehicles are closely related to the use of space on a given construction site. Furthermore, low productivity is frequently a result of poor site planning, which also leads to conflicts between subcontractors. Thus, better spatial organization is critical for achieving work safety and high productivity. Here, one has to capture the existing site conditions in order to analyze the site layout. Thus, there is a strong need for accurately capturing the existing condition of a construction site for efficient and effective space planning.

This research explores various traditional and advanced methods such as 2D drawings, photo-modeling and laser scanning for capturing as-built site conditions. The next section explains limitations related to documentation of construction site using 2D drawings and 3D laser scanning. Furthermore, practical and technical issues related to the data acquisition are also explored, which lead to the problem statement and objectives of this research. In order to overcome problems related to the current research, objectives of the research are explained in the next section. The third section describes the overall methodology of automating the process of capturing as-built site conditions for space planning purposes. The last section briefly explains the overall structure of the report.

1.2 Problem Statement

The need for capturing existing site conditions and possible data acquisition techniques are illustrated in Figure 1. Traditionally, collecting site as-built information is done informally through actual field observation and measurement conducted by project personnel, which can be time-consuming and inaccurate at times (e.g. Golparvar-Fard et al., 2011). Furthermore, once field data is collected, 2D drawings are commonly used for documenting and representing site conditions for various purposes, such as space planning, material logistics, and safety management. However, spatial issues related to construction activities and resources are by nature a three dimensional (3D) problem. 2D drawings pose great limitations for these spatial-related construction management issues that are best represented and analyzed in a three dimensional space. Moreover, frequent and sometime abrupt changes on the job site, such as location changes of major equipment and material storage, warrant frequent measurement and representation of the current site space.

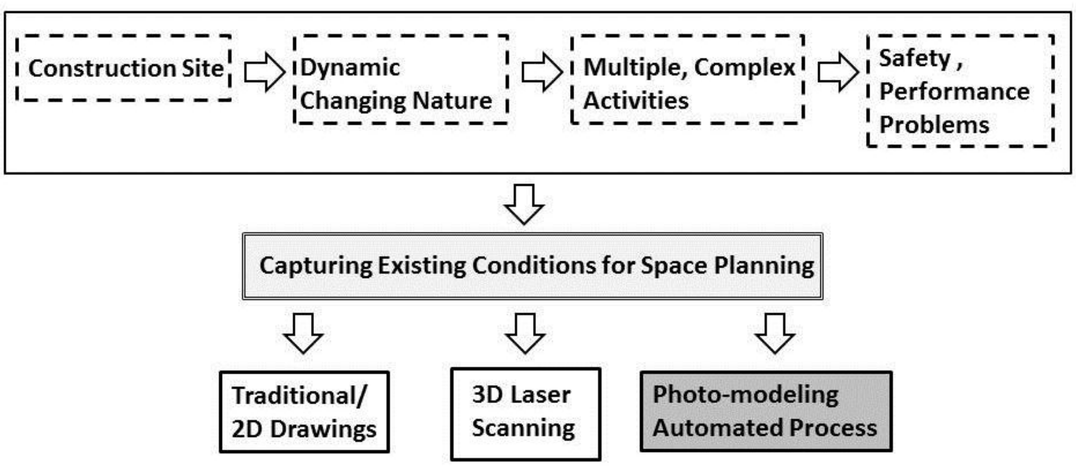


Figure 1 Different techniques for capturing existing conditions

With recent technological advancement, 3D model reconstructions from laser scanning and photo-modeling techniques are used for capturing as-built conditions of a construction site (El-Omari and Moselhi, 2008). Laser scanning is a highly accurate technique for capturing existing conditions but has limitations related to the number of scanning positions required, high cost of equipment and requirement of trained personal. Another technique, called photo-modeling, is used for deriving 3D virtual models from 2D images. However, laser scanning has several limitations for its use for space planning, where constantly changing site conditions must be captured frequently. The limitations include a large number of scans and considerable amount of time required, high cost associated with the equipment, and the need for a trained personal to process the collected data (El-Omari and Moselhi, 2008). These limitations make laser scanning less favorable for daily field use for capturing as-built information and space planning purposes. An alternative technique, photo-modeling provide a way of extracting data in a form of point cloud from 2D photos and then mapping the data into a 3D geometrical space. However, some barriers related to stitching of 2D images and reconstruction of a 3D model exists. In particular, in order to obtain a comprehensive view of a site, a large amount of acquired photos must be matched together. This matching can be traditionally achieved with two means. The first method involves the use of artificial markers which must be applied to various locations of the site prior to photo shooting (Photo-modeler, 2011). The other method requires manual matching of 2D images by users. Due to the significant amount of time and efforts required in these methods, their application to site planning, where frequent photo processing is required, is not practical and cost-effective, if not impossible. Therefore, there is a need for an efficient and cost-effective method for capturing site as-built information for space planning.

1.3 Objective

As mentioned in the previous section, we have explored various limitations related to the manual matching of images for as-built data collection. Thus, the main objective of this research is to propose a photo-modeling based framework for automatically stitching site photos and providing users a 360-degree view of the site in a personal computer. In addition, the point clouds derived from the photos will be automatically extracted and used to produce a 3D construction site modeling for space planning. This automated photo-modeling approach is intended to be an efficient and cost-effective approach for capturing existing conditions of a construction site for space planning, such as site traffic plan, conflict avoidance, and look-ahead scheduling.

1.4 Methodology

The proposed automated field as-built capturing and modeling process is achieved in four steps. The first step involves image acquisition of a construction site using a portable digital camera. The second step develops a procedure for photo stitching and point cloud data generation using a computer-vision algorithm, “Photo tourism” (Snavely, Seitz and Szeliski, 2006), to develop a 360° view of a site. This algorithm introduces the concept of photo stitching based on image feature points and Structure from Motion (SfM) algorithm. The next step is to export 3D point cloud into 3D modeling software in order to derive a 3D surface model of a construction site. This research explores different 3D surfacing algorithms and proposes a point cloud skinner algorithm for automatic surfacing of objects. The fourth and the last step utilize the 3D surface model for space planning purposes. A prototype of the proposed system is implemented. Open source software tools are used for implementing this prototype system. The use of these open source tools provides opportunities for better integration of different stages of the proposed system, while reducing the overall cost of the system.

A real-world case study will be conducted to demonstrate the proposed system and verify its feasibility. In particular, this case study intends to capture existing conditions of a construction site in the form of a 3D virtual construction model, which is used later for identification of material storage conflict on the given construction site.

1.5 Thesis Organization

This report is organized into five chapters, including this introductory chapter. Chapter 2 explores previous research in the form of literature review. It first discuss the current industry practice of spacing planning, followed by a discussion of recent developments in photo-modeling, the use of 3D laser scanning for capturing existing site conditions, limitations and advantages related to laser scanning, and photo-modeling and comparison between photo-modeling and laser scanning techniques. The proposed photo-modeling based and automated as-built construction site modeling system is explained in the Chapter 3. Four important stages of the methodology are explained in detail. Furthermore, this chapter explains the main ideas behind photo modeling, , point cloud extraction, and automatic surfacing algorithms, as well as the use of open sourced software tools. A prototype system and its validation through a real-world case study is presented in Chapter 4. The conclusion, lessons learned and future research are discussed in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

This section discusses the current practice of space planning, its advantages, and limitations. It also explains past studies related to 3D model reconstruction using photo-modeling and laser scanning techniques. This chapter also compares photo-modeling technique with laser scanning and summarizes the outcomes of the literature review in the last section.

2.1 Space Planning

Akini at el. (2002) explains time-space conflicts and identifies six types of spaces for time-space conflict analysis. The research states that space is a critical resource at construction sites. Furthermore, the space-time conflict occurs frequently and has a significant impact on the productivity and overall construction process. Moreover, research mentions six types of spaces, including building component space, labor crew space, equipment space, hazard space, protected space and temporary structure space. These spaces have high frequency of space-time conflicts and thus gain importance for space-time conflict analysis. Akinci at el. (2002) mentions that shorter delivery schedules leads to increase in space per unit time which results in space conflicts. Thus, the importance of space planning becomes clear from the literature review.

Another research deals with the space planning and 3D virtual simulations. Zhang, Maz and Cheng Pu (2001) states strong need of visual and intelligent management of the construction site. It explains the concept of graphical simulation of the work plan for early problem identification. The visual representation will help non-professional to clearly understand site management process. It also introduces the concept of linking virtual 3D models with scheduling software. Furthermore, Waly and Thabel (2003);

Karray F. et al (2000) mentions an innovative idea of inserting ready-made blocks within 3D modeling software. It also explains an important observation such as models for layout planning related to site and facilities are based on basic geometrical figures like rectangle.

In summary, space planning is performed using 2D drawings. Waly and Thabet (2003) mentioned the limitations of the manual approach of visualizing and understanding site space, such as 2D site layout drawings, 2D scaled models, and, in some cases, 3D physical models. As a result, many researchers stressed the need of developing 3D virtual construction sites, which could be used for pre-construction planning, including site access, facilities locations, and storage areas (e.g. Zhang, Maz, and Cheng, 2001). The following sections review recent development of applying laser-scanning and photogrammetry based methods for capturing and representing construction site conditions in a 3D format.

2.2 Laser Scanning

There are several ways in which laser scanning can be performed such as aerial, mobile or terrestrial laser scanning. Due to the requirement of close range and high precision measurements for construction sites, terrestrial laser scanning technique is used for capturing existing conditions of a construction site (Golparvar-Fard et al, 2011). Generally, Laser Detection and Ranging (LADAR) term is used for 3D laser scanning systems. In this case, scanning equipment takes multiple distance measurements within a scene to derive an output in the form of a 3D point cloud model. Another type of 3D laser scanner called flash LADAR or a 3D video range camera uses a single light pulse from a broad-field illumination source to capture dynamic conditions in a real time scenario

(Randall, 2011). Figure 2 shows types of 3D laser scanning equipment, Leica scan-station high definition scanner and Surphaser 3D terrestrial laser scanner. Laser scanning is a highly accurate technique for capturing as-built conditions based on the principles of range, intensity and time of flight for acquiring measurements for distinct points in the scene. Scanning equipment sends illumination pulses towards an object and measures the return time of the signal so that the object's location and distance can be measured. The outcome of the scan is a point cloud data which is visualized through commercially available software. Another advantage is the availability of dense point cloud data which can be manipulated in order to derive a virtual environment for given construction site scenario. For example, the laser scanner derived point cloud models have been used for progress measurement and monitoring. Laser scanning is a highly accurate technique for capturing as built conditions (Golparvar-Fard et al ,2011). However, laser scanning has various limitations like number of scanning positions are needed to acquire accurate information, high cost associated with the equipment and need for a trained personal to process the data (El-Omari and Moselhi, 2008). Though laser scanners can derive high resolution models, they are limited by the fact that it increases overall size of the data file and processing time. Furthermore, Laser scanners also require significant power, regular calibrations as well as warm up time (Golparvar-Fard et al., 2011; Golparvar-Fard, Pena-Mora and Savarese, 2009).

(a) Leica scan-station high definition scanner

(b) Surphaser 3D terrestrial scanner

Figure 2 3D laser scanning equipment

2.3 Photogrammetry and Photo-Modeling

Photogrammetry was traditionally used as a technique for site surveying. During early days of photogrammetry, special camera and equipment are required and photogrammetry was entirely a manual process. Transition was observed from terrestrial photogrammetry to digital photogrammetry because of the advancement of digital image capturing technology (Waldhausl, 1992). Photogrammetry can be divided into two categories such as aerial and terrestrial. Terrestrial photogrammetry is used for the construction sites because of its capacity for acquiring images near or on the surface of the earth. If the object size and camera to object distance are both less than 330 ft, then terrestrial photogrammetry is defined as close-range photogrammetry (Jiang et al, 2008). Figure 3 illustrates the concept behind close range photogrammetry. The fundamental principle behind photogrammetry or laser scanning is triangulation as shown in Figure 4. An object feature is observed from two different views such that two corresponding lines of sight are intersected in space. This helps in the identification of a three-dimensional co-ordinate of an object feature. In the case of laser scanner, one uses projector in order to facilitate triangulation, whereas in the case of a digital camera, projector gets replaced by another camera position. Dimensions of the triangle are calculated by known values of α, β and D (Jean-Anglo, 2004). α is the angle of incidence, β is the angle between the base line and reflected ray, and D is the distance between optical center and the intersection of the incidence ray and base line.

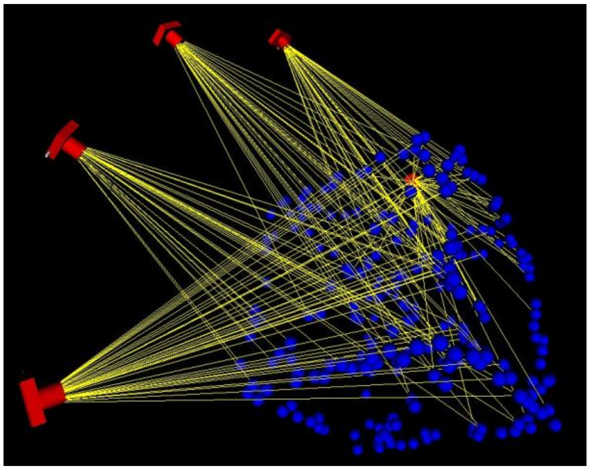


Figure 2 Close-range Photogrammetry

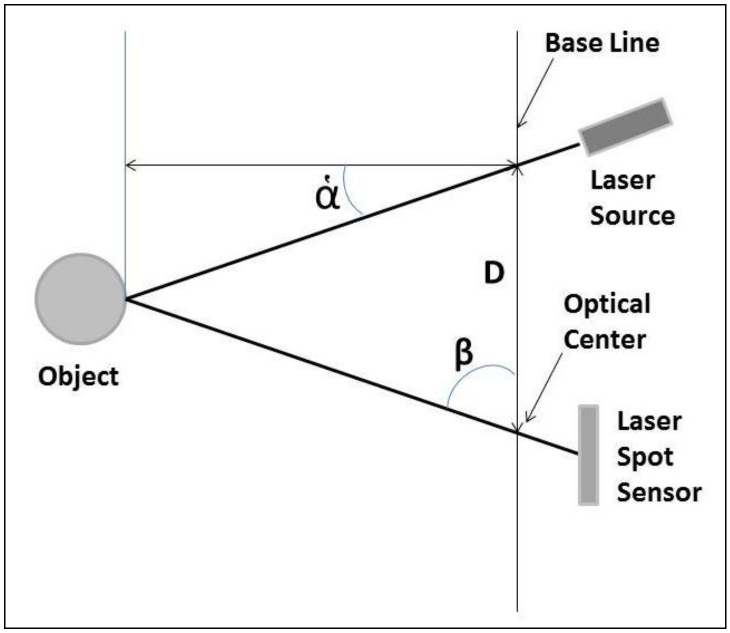


Figure 3 Laser-based optical triangulation (Jean-Anglo, 2004)

Diverse applications of photogrammetry can be found in the field of industry, archeology, architecture and aerospace engineering (Jiang et al, 2008). Dai and Lu, 2008 explain the application of photogrammetry related to construction sites. In case of construction field, photogrammetry was applied for the documentation of site conditions by using daily photo logs. By using site photos, a particular situation of a site having building materials, construction resources and site layout can be easily captured and documented.

The modernized photogrammetry, photo-modeling technique, makes possible the use of 2D photos taken by a digital camera for creating a 3D point-cloud model. Sami, El Omri, and Moselhi (2008) discussed the advantages of photogrammetry-based approaches, such as its ability to acquire close range data and clarity in defining object edges. Golparvar-Fard et al. (2011) compared point cloud models generated using photogrammetry technique and one that was generated from high precision laser scanners. For creating 3D as-built models, while the accuracy of the photo-based point clouds is less than that of the laser scanning point clouds, the photo-based approach do not add burden on project management teams by requiring expertise for data collection or analysis as in the case of laser scanning. Golparvar-Fard, Pena-Mora and Savarese (2009) focused on the reconstruction of a 3D model of a structure using geo-registered photos. Another research by Brilakis, Fathi and Rashidi (2011) focused mainly on the progressive 3D reconstruction of infrastructure using videogrammetry. It also explains the advantages and disadvantages of various image capturing techniques, such as laser scanning, photogrammetry and videogrammetry. It also emphasizes the requirement of minimum human intervention while processing the data and manual matching of 2D photos to derive a 3D model. Figure 5 illustrates a 3D model developed in Autodesk Photo Scene Editor which is photo-modeling software.

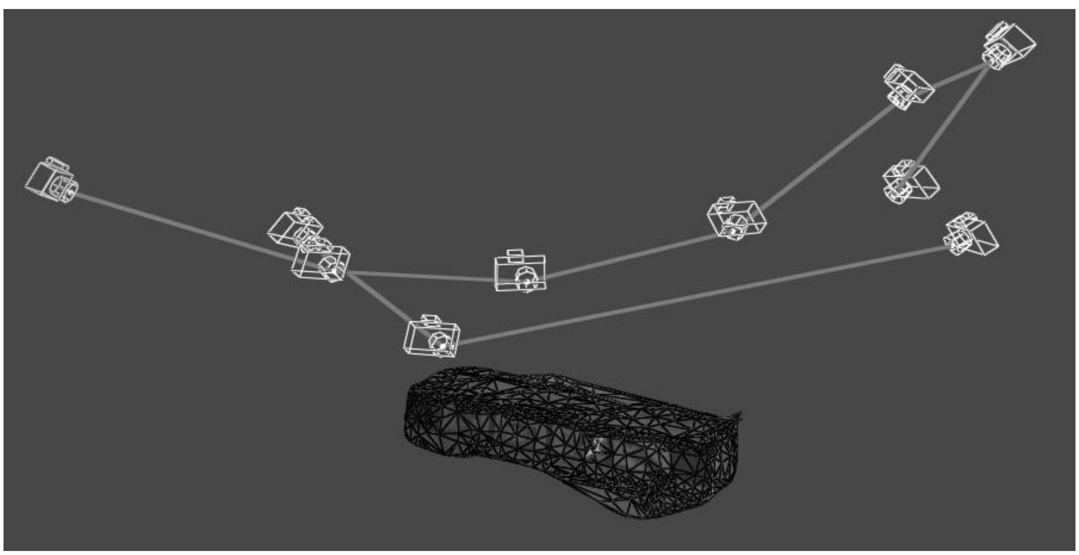


Figure 4 Photo-modeling using Autodesk Photo-Scene Editor.

2.4 Comparison of Photogrammetry and Laser Scanning

Recent development of 3D reality-capturing technologies, such as 3D laser scanning and photogrammetry, allows an accurate measurement and representation of a job site (El-Omari and Moselhi, 2008). However, laser scanning has several limitations for its use for space planning, where constantly changing site conditions must be captured frequently. Compared with laser scanning, photo-modeling is considered to be a more cost-effective technique, which takes less time to collect and process the data, and in case of physical limitations, enables close range data acquisition (El-Omari and Moselhi, 2008). Laser scanning requires multiple scanning locations and scans for deriving point cloud models which increases image acquisition time whereas photo-modeling technique uses images acquired from digital camera which takes less time compared to laser scanning. Furthermore, laser scanners use heavy equipment whereas in the case of photo-modeling, a handy and portable digital camera is used for image acquisition. Laser scanner requires a trained personal for data acquisition and its processing. However, a layman or a construction worker can easily use photo-modeling technique without prior training. Table 1 shows the overall comparison between photo-modeling based point cloud model and laser scanning based point cloud model (Golparvar-Fard et al, 2011).

The comparison reveals important facts as explained further here. In the case of laser scanner derived point cloud model, manual intervention is required for noise reduction and removal of unnecessary point cloud data. However, in the case of photo-modeling, the data processing may be automated. Another area of comparison is related to the training requirement of the equipment. No formal training is required for implementing photo-modeling technique, whereas special training is required for laser scanning and processing of the 3D point cloud data. In summary, it is evident that there are several advantages related to the use of photo-modeling technique which supports objectives of the current research and can be used for capturing existing conditions of a given construction site.

Table 1 Comparison of Photo-modeling based point cloud model vs. laser scanning point cloud model (Golparvar-Fard et al, 2011)

		Laser Scanning Point Cloud model	Photo-modeling based Point Cloud model
Cost	Data Collection Cost	8 ~16 man-hours *	0 ~1 man hour
	Data Processing Cost (Registration)	O** (s)	O (min ~h) on a single machine+ O (min) with parallel computing
	Technology Implementation Cost	O (10,000 ~130,000 USD)	Cost of Consumer Camera O (100 ~500 USD)
Alignment of photos with point cloud model		Manual	Fully Automated
Applications		• Alignment / Defect inspection • Static progress visualization • Static safety analysis	• Remote visual inspection • Remote decision making • Static / dynamic progress visualization • Site Logistics visualization • Construction crew and machinery productivity analysis • Static / dynamic safety analysis

2.5 Observations and Summary

Majority of past researches focused on the implementation of space planning using laser scanner to derive 3D models and its use for construction progress monitoring. An important observation from the literature review is related to the complementary nature of space planning and photo-modeling. Space planning can be effectively performed by using basic geometrical forms and photogrammetry provides an approximate 3D model of a construction site. Thus, this observation strongly supports the idea of using photo-modeling for the space planning. Literature review also shows the use of ready-made 3D blocks for 3D visualization purposes. Current research proposes surface modeling in order to improve visualization of 3D environment and make it more realistic. In the case of laser scanning, commercially available software is utilized for data processing. Our research goes a step ahead and tries to utilize open source software related to photo-modeling in order to reduce the cost associated with the software.

In summary, past studies not only confirmed the efficiency and cost-effectiveness of the photo-modeling based technique when compared with 3D laser scanning but also the importance of space planning and the effectiveness of 3D virtual modeling technique over traditional methods for space planning. They have motivated our research in applying the photo-modeling technique to construction site space planning. To streamline the space planning process using photo-modeling, this research is to develop an automated process for stitching 2D photos to derive a 3D reconstructed model of a construction site with a minimum level of human intervention.

CHAPTER 3: AUTOMATED AS-BUILT CONSTRUCTION SITE MODELING

The proposed method provides an integrated approach in acquiring images, matching imaging, extracting point clouds, generating 3D surface models, and modeling construction space for planning purposes. Recent advancement in computer vision, digital photography and 3D modeling techniques make possible the automation of this reality-capturing and modeling process while minimizing human intervention. The proposed integrated and automated process is achieved in four steps as described in Figure 6. The first step involves acquisition of 2D photographs using a digital camera. These 2D photos are then stitched together in the form of a panoramic view. This step also helps in deriving 3D point cloud model of a given construction site. In the next step, 3D surface model is developed from the 3D point cloud model. The final step utilizes 3D surfaced model for space planning purposes. This research also explains various alternatives this research explored while developing the proposed system.

As mentioned previously, the current research tries to integrate open source tools. The most important requirement for open source software is the free availability of its source code which can be examined or modified by anybody to suite its own purpose (Godfrey and Quiang, 200). Thus, our main intention is to use the customization feature of the open source software in order to achieve the complete automated process. Integration of different programs and codes is one of the advantages of using open source software. This is possible because of the capacity to customize certain codes and programs (Neves, Machado and Shiyou, 2011).

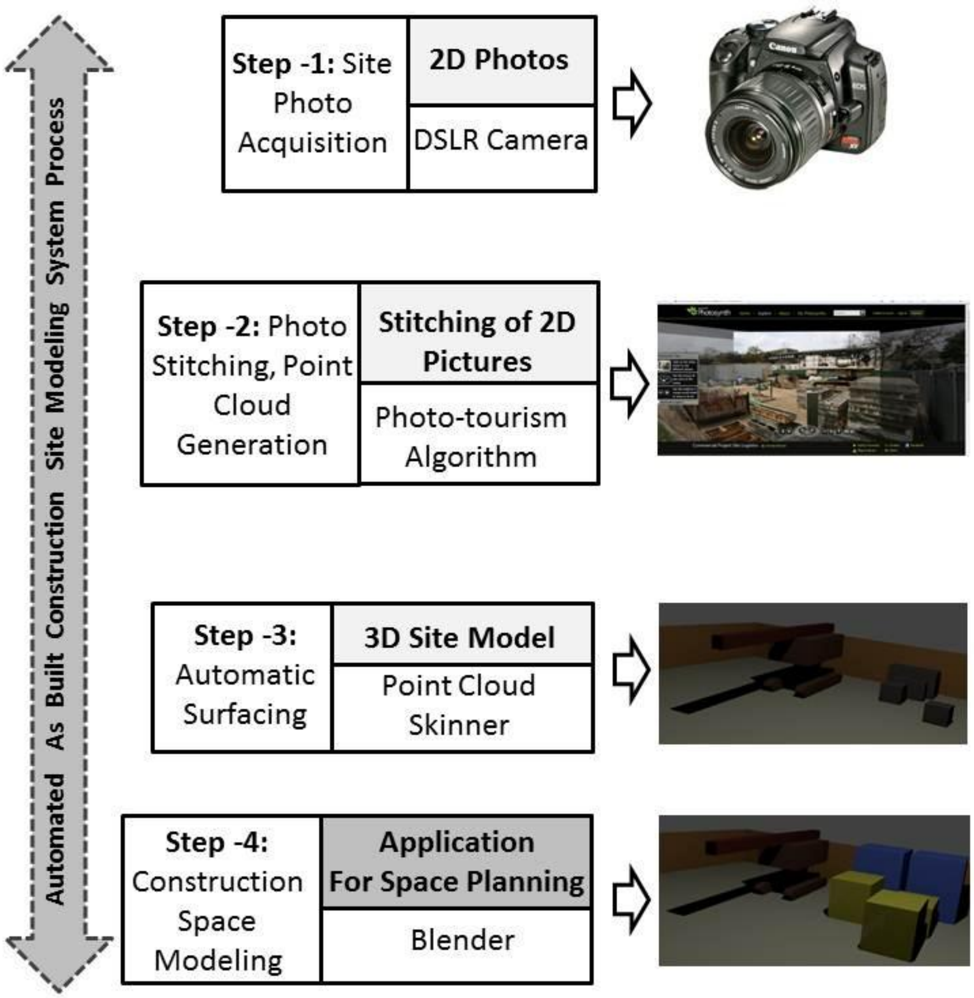


Figure 5 Overall framework for automatic as-built system process

3.1 Site Photo Acquisition

The first stage involves collecting images with overlapping features from a construction site using a generic digital camera. In order to support subsequent image matching and point cloud extraction, which is described in details later, it is important to follow the rule of "three", which states that each part of the scene appears in at least three separate photos taken from different angles. Also, for better results one needs overlapping rate of more than 50% between subsequent photos. The strategy for capturing photos will defer from the interior spaces to exterior spaces. In general, depending upon the area that needs to be captured and placement of objects, it is recommended to take as many overlapping photos as possible. While capturing the site conditions, it is desired that photos be taken every 25°. It is highly recommended to shoot wide angle shots in order to capture panoramic view of the scene. For effective image matching and point extraction, it is also important that scenes are captured having lots of details and textures. Some intermediate photos should be captured to show object details and its spatial relationship to other portions of the site. Detail photos help to derive dense point cloud of the respective object. Figure 7 shows the camera locations for shooting a 3D object. These instructions for shooting object are the recommendations which can be easily followed by a construction worker or a layman and does not require special training. It is highly recommended to take sufficient Photos of the given scene because larger number of photos will increase the accuracy of modeling.

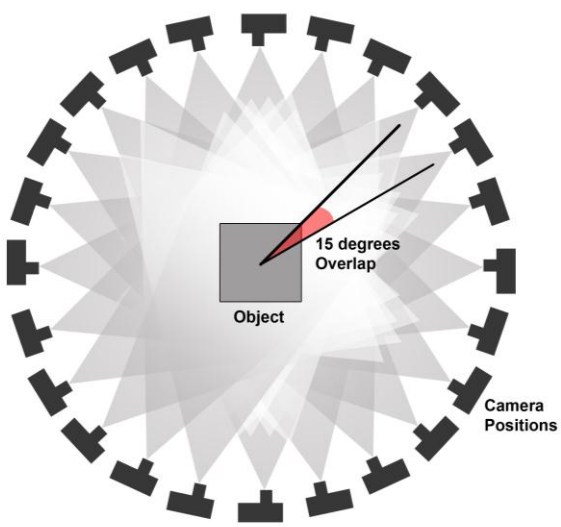


Figure 6 Diagram showing shooting of 3D object

3.2 Photo Stitching and Point Cloud Generation

In the second stage, we adopted a computer-vision algorithm, titled "Photo-tourism", for image matching and point-cloud generation (Snavely, Seitz and Szeliski, 2006). Photo-tourism is an image-based modeling and rendering technique for transforming a set of related photos of a scene into an interactive 3D environment for photo browsing. Through an optimization process, large collections of unorganized photographs but with overlapping features are stitched together according to their matching features to derive a 3D geometric representation of the target scene as shown in Figure 8. It also creates a new interface for browsing large collections of photographs aligned in a 3D environment for easy viewing. This concept has been successfully applied to document some of the world's prominent and highly visited sites and resulted 3D representation has been shared with online surfers for a virtual tourism experience (Snavely, Seitz and Szeliski, 2006).

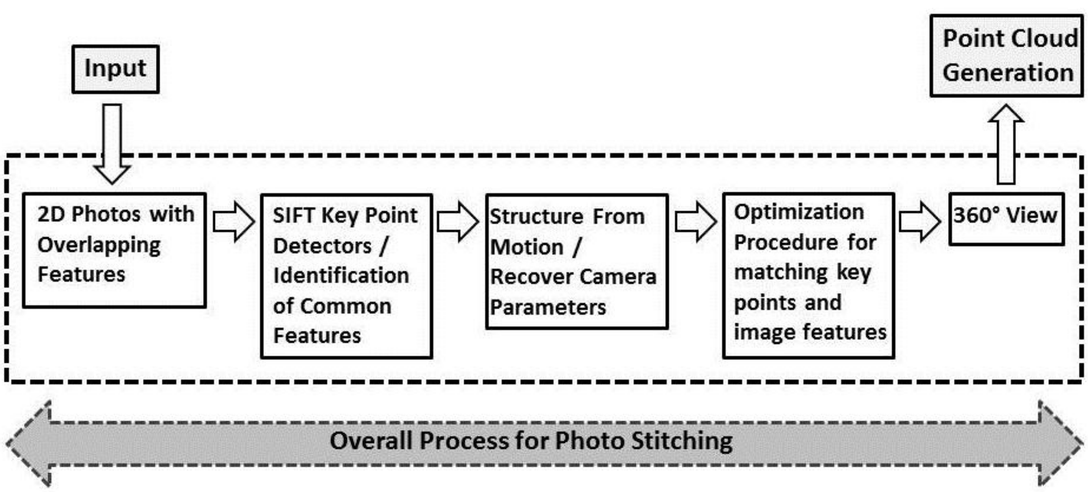


Figure 7 Diagram showing overall process of photo stitching.

In order to match photos, Photo-tourism first identifies feature points in each image, such as corner points and edges. In the first stage, Scale Invariant Feature

Transform (SIFT) key-point detectors are used to identify feature points. Its main approach is to transform image data into scale-invariant co-ordinates relative to local features in an image. SIFT features are extracted from a set of subsequent images. Image matching is performed by comparing each feature in order to derive common feature points (Lowe, 2004). These geometrically consistent matches between each image pair is organized into tracks, which is a set of matching key points across multiple images. Furthermore, a Structure from Motion (SfM) procedure is applied to recover the camera parameters, such as location and focal length. The main concept is to derive a common 3D co-ordinate system as images have different camera parameters. Finally, the camera parameters and 3D positions of those features are recovered by running an optimization based on the minimization of the distance between matching key points and its corresponding image features (Snavely, Seitz and Szeliski, 2006).

While Photo-tourism provides users an immersive 360 degree view of a scene, this visually-pleasing view has limited use for 3D modeling and measurement, such as the case of site space planning, where existing site objects must be modeled as 3D shapes and planned materials and equipment objects can be inserted by users. In other words, for construction space planning, there is a need to acquire the geometrical data hidden behind the 3D photo view so that they can be used to reconstruct a 3D as-built model of a site. Fortunately, while matching photos and generating the 3D photo view, Photo-tourism also generates a set of space coordinates of feature points identified through its data analysis process. These feature point data resembles point-cloud data generated by 3D laser scanning, and they can be extracted and used to derive 3D as-built models of a construction site.

An alternative approach to Photo-tourism is Photofly developed by Autodesk (2011). Photofly is a fully automated, end-to-end 3D modeling system in which digital photographs as an input is used to develop 3D virtual models. Photofly also generates 3D point cloud as an intermediate step and uses texture mapping algorithm for object surfacing (Photofly, 2009). Figure 9 shows 3D virtual model of a construction site developed by using Autodesk Photofly. It has several advantages in regards to the surfacing of the object and texture mapping compared with Photo-tourism. However, it does not display the point cloud data and does not have the capability of object editing and animation, which makes it unsuitable for this research.

In addition, comparing with the approach of using geo-registered photos (e.g. Golparvar-Fard, Pena-Mora and Savarese, 2009), our approach of using Photo-tourism does not require GPS or other specialized equipment. Thus, no other equipment is required for capturing existing conditions other than a handy digital camera (Snavely, Seitz and Szeliski, 2006). This approach is even more cost-effective when considering the fact that expensive user training is not necessary. For the above reasons, Photo-tourism is used in this research.

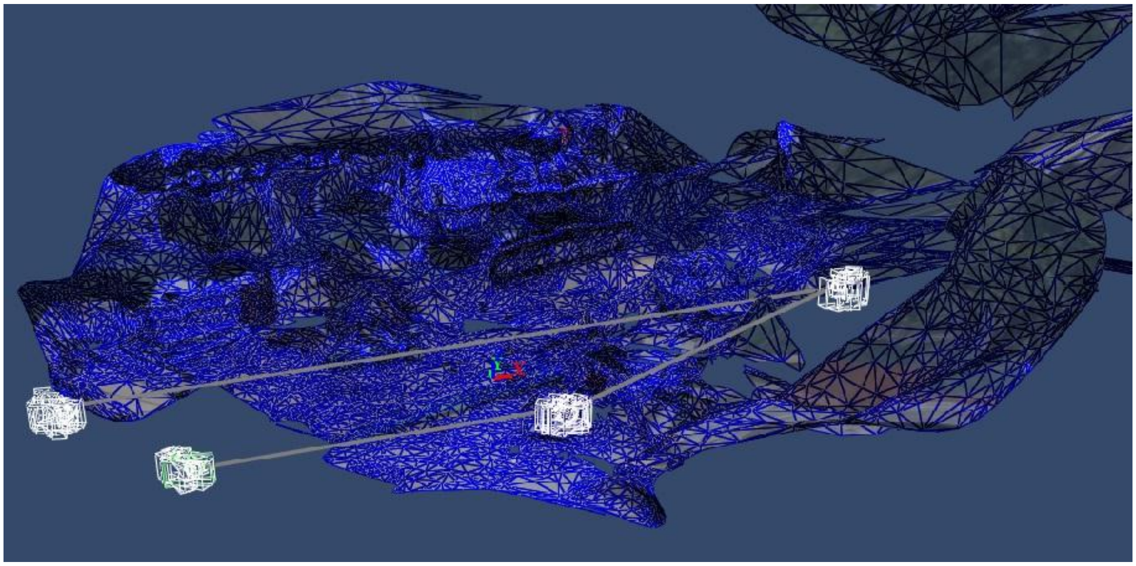


Figure 8 3D virtual model of a construction site in Autodesk Photofly.

3.3 Automatic Surfacing

While point cloud data is useful, they only represent discreet points in a 3D space coordinate and each individual point carries very limited information that can be used for space modeling and planning. To represent objects or space occupied on a job site, we need to link a group of points that represent an object or a geographical shape. Although this work can be done manually, such as the case for manual point-cloud processing in 3D laser scanning, this manual process would be too time-consuming for construction applications. Therefore, there is a clear need for an automated process for deriving the point clouds and model them as 3D surfaces that can be used later for spatial analysis. This not only requires less computational time but also helps in achieving overall objective of this research by automating the entire process. Several algorithms, such as point cloud skinner and ball pivoting algorithm, are used for object surfacing (Point Cloud Skinner, 2007). Our intention is to use this algorithm to generate auto-surfacing for the point-cloud data obtained from the previous step. These candidate algorithms are discussed in the following section.

Ball pivoting algorithm is mainly used to derive triangulated mesh that is made up of triangular shape having three edges. The main concept is to join a number of triangles to obtain a complete meshed object. The algorithm searches a source or a seed triangle within existing data points. A ball is pivoted around each edge within the current mesh till a new point is hit by the ball. A ball is made up of spherical space of defined radius. This edge and the point define a new triangle which is added to the existing mesh. This process continues to add different edges and points to derive a complete mesh object (Bernardini et al, 1999). At this stage of the research, our preliminary test showed that the ball pivoting algorithm performs well only for areas where dense point cloud is observed. Figure 10 shows one of the attempts of surfacing given object from a construction site. In addition, to surface an entire site, the ball pivoting algorithm is unable to differentiate among different objects and tries to connect points from different objects.

Therefore, in this research, we adopted the point cloud skinner algorithm. This algorithm selects the center of a cluster which is formed from a number of vertices. Then, it measures the minimum distance between the center and individual vertex. The next step is to join closest vertex with the center. This process is repeated for entire model in order to surface the individual object as shown in Figure 11 (Point Cloud Skinner, 2007). Our approach is to use this point cloud skinner algorithm to derive 3D surfaced model of the entire construction site Also, it should be noted that open source tools, such as point cloud skinner in this case, are used in this research because they are free available and provide an excellent opportunity for integrating with other modeling tools and 3D software for a fully automated system.

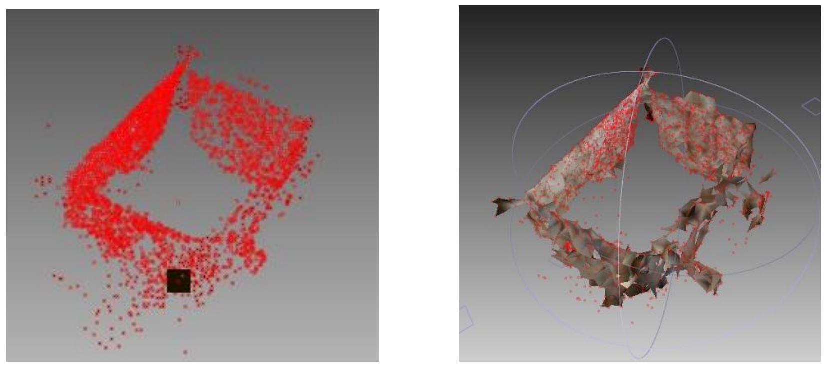


Figure 9 Surfacing of an object using Ball Pivoting Algorithm

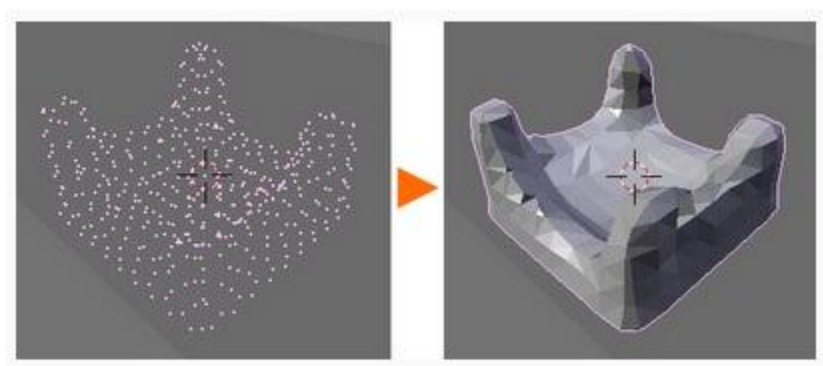


Figure 10 Surfacing of object using Point Cloud Skinner algorithm

3.4 3D Construction Space Modeling

The ultimate goal is to use 3D surfaced model for space planning. Since, the surface model efficiently captures the existing conditions on site; it can be effectively used for measurement purposes, such as distance, height, volume, and spatial relationship among objects, as well as for progress measurement and safety management related activities. Various applications are made possible by developing virtual scenarios, such as planned equipment and materials can be modeled as 3D objects or imported from other CAD modeling systems, such as Google Sketch Up. With the site as-built model and the capability to insert virtual planned 3D objects, users can plan the movement of major equipment, such as a mobile crane, around the site, and analyze potential spatial conflicts, such as heavy lift operations. This 3D site model can help to accurately forecast the change of construction site space along the project timeline. In addition, users can perform more effective look-ahead scheduling that accurately identifies space constraints, such as material storage issues. The current research also explores the possibility of linking project schedule with a 3D modeling software in order to achieve efficiency in the case of space planning. Another possibility is to define different zones around the site to represent the space needed to perform an activity. When the time schedule is linked with each activity zone, users can identify activity space conflict or safety issues. For example, area surrounding excavation pit represents a zone which is the space required for the excavation activity. Due to productivity and safety concerns, this zone should not be used by any other activity or resources until the work is done. The feasibility and effectiveness of the proposed approach is demonstrated in the following real-world case study.

As mentioned previously, the current research tries to integrate open source tools. The most important requirement for open source software is the free availability of its source code which can be examined or modified by anybody to suite its own purpose (Godfrey and Quiang, 200). Thus, our main intention is to use the customization feature of the open source software in order to achieve the complete automated process. Integration of different programs and codes is one of the advantages of using open source software. This is possible because of the capacity to customize certain codes and programs (Neves, Machado and Shiyou, 2011).

In summary, this research is intended to integrate the photomodeling knowledge from the computer science filed and apply it to construction management functions, such as space planning in this case. The main contribution is to develop the overall methodology of image processing, integration, and automation. Another contribution is the identification and application of open-source tools to support objective of the research and deliver an automated data capturing and 3D modeling process. In this particular case, series of open sourced software tools are used to derive the entire automated process. Furthermore, it is important that the individual software functions must be integrated seamlessly to achieve a true automated process.

CHAPTER 4: CASE STUDY

The case study was conducted on a construction site located on the University of Houston main campus (Houston, Texas) in order to validate the proposed system. This project involves the expansion of the university's central plant, where chillers are being installed within the existing setup of the power plant. Figure 12 shows the key layout of the construction site. The built-up area for expansion is 8,000 sq ft at an estimated cost of $45 million. The following sections describe the four important steps involved in the automation process, lessons learned and the results. It should be noted that open source programs were used as much as possible in the development to provide opportunities in future system integration.

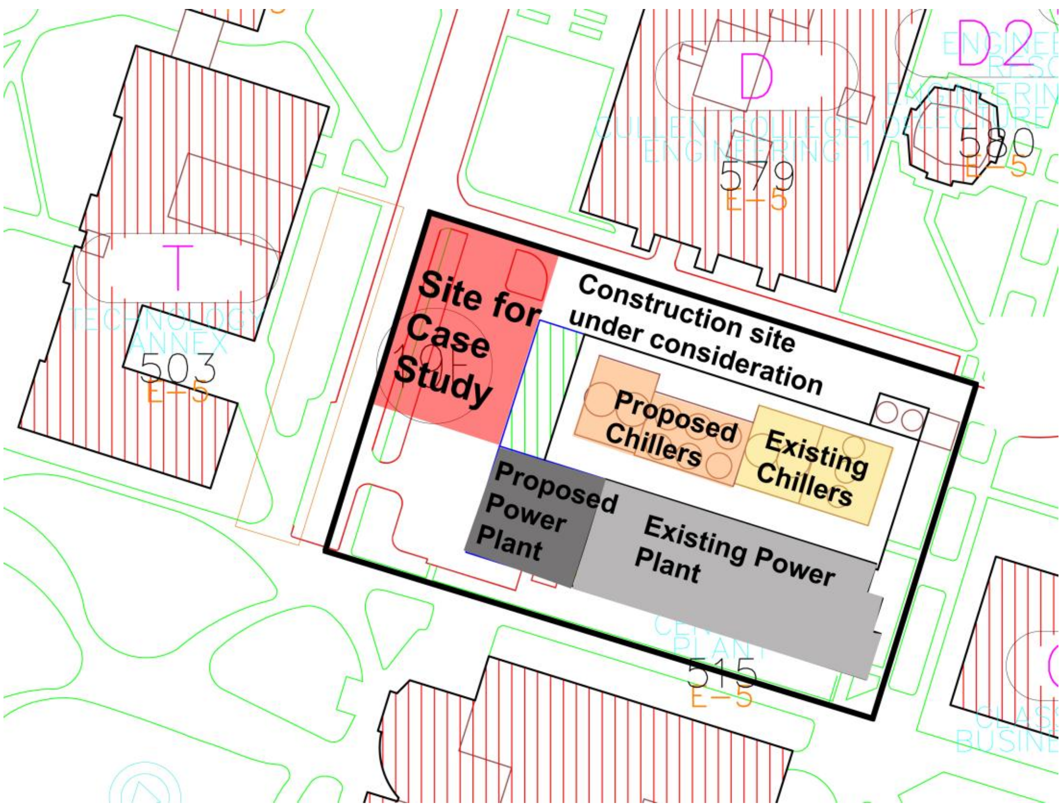


Figure 11 Key map showing the case study construction site

4.1 Step 1: Site Photo Acquisition

During site data collection, images were taken using a Cannon Digital Single-Lens Reflex (DSLR) camera. A strategy was formed to take pictures along the periphery of the site and important objects were photo documented. For this initial case study, over 100 2D images were captured, as demonstrated in Figure 13. As previously discussed in chapter 3, general rules of photo documentation were followed for capturing the images such as rule of 3 and 50% overlapping of the photos. In order to capture an entire job site, detailed photo documentation of all important objects on a construction site is required. More photos with overlapping features can also help in deriving a finer grained 3D point-cloud model. As discussed previously, a limitation observed during this stage is the attempt to capture a large construction site. This challenge can be overcome using a piecewise approach in which the entire site is modeled piece-by-piece and these pieces are then combined later in a single 3D model as shown in the Figure 14.

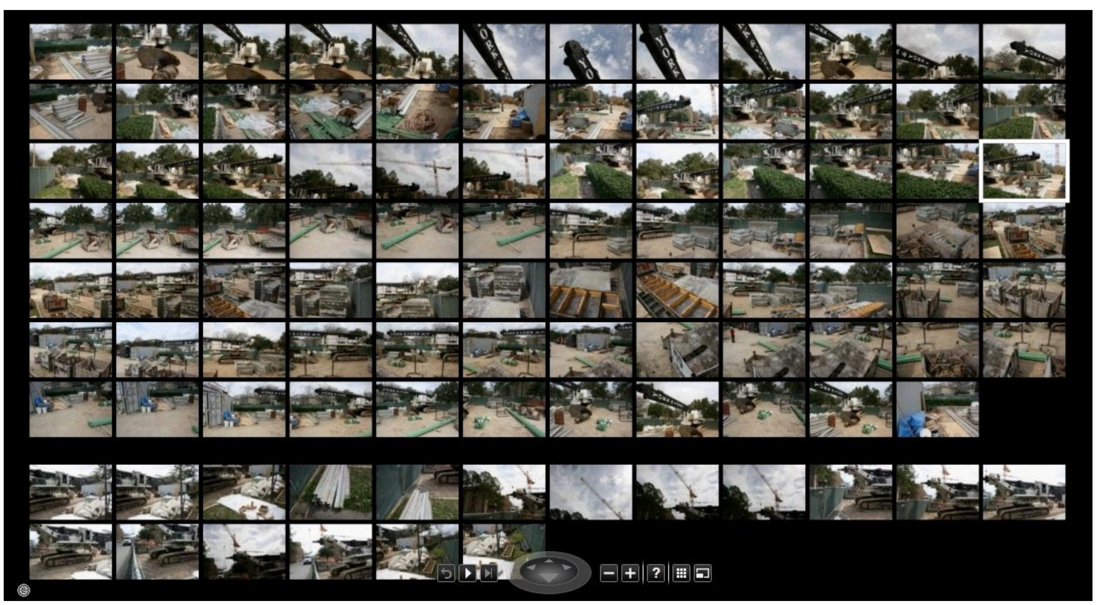


Figure 12 Captured images from a construction site

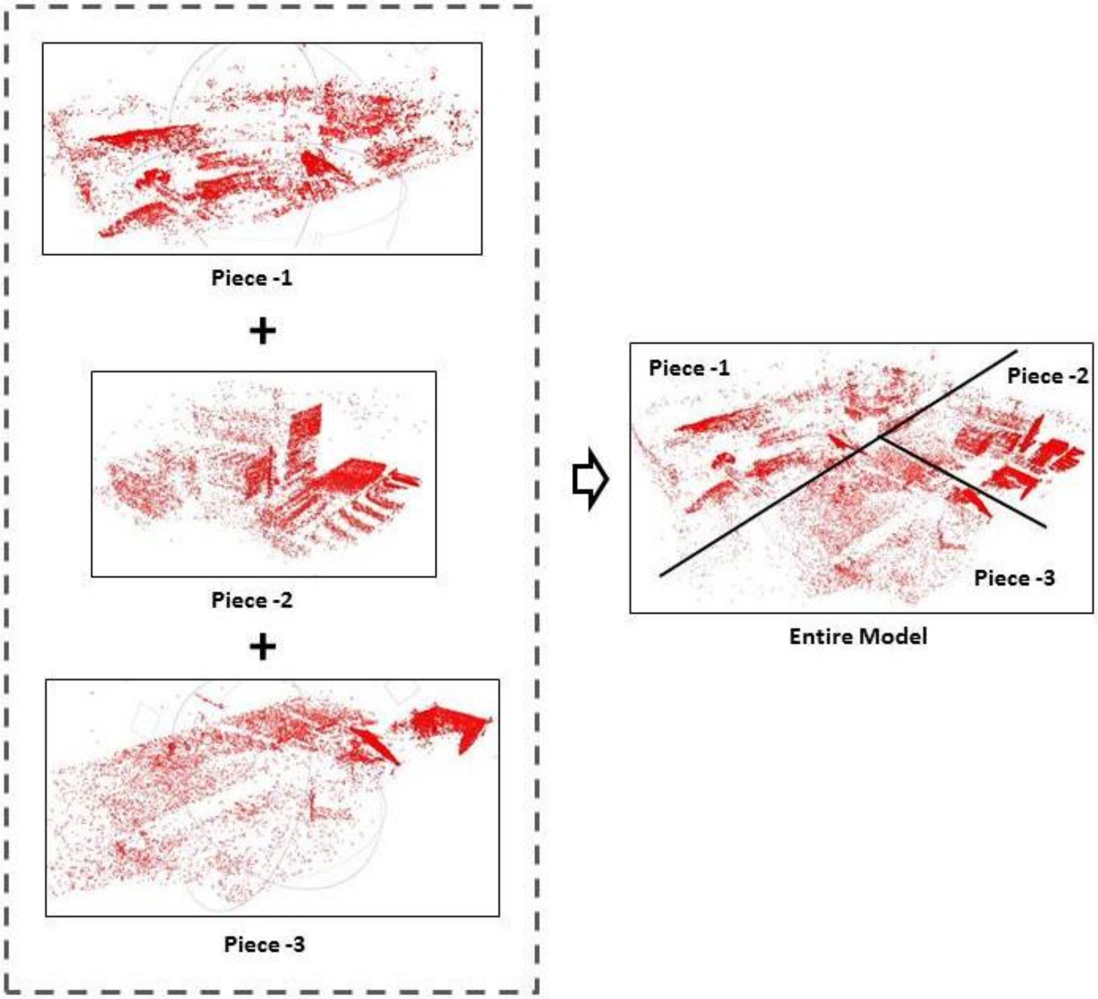


Figure 13 Piece-by-piece approach for combined 3D model

4.2 Step 2: Photo Stitching and Point Cloud Generation

This step involves stitching of 2D images by using photo-tourism algorithm. One of the photo-tourism implementations that are commercially available is Photosynth (Microsoft Photosynth Network, 2011). All captured 2D images from the construction site were imported to the Photosynth web server from a personal computer as shown in Figure 15. 84 % synth rate, a measure of the percentage of matched images, was achieved, and Figure 16 (a), (b) and (c) shows different portions of the resulted 3D photo view. The outcome of this step is a 360° view of the construction site which is navigable within Photosynth.

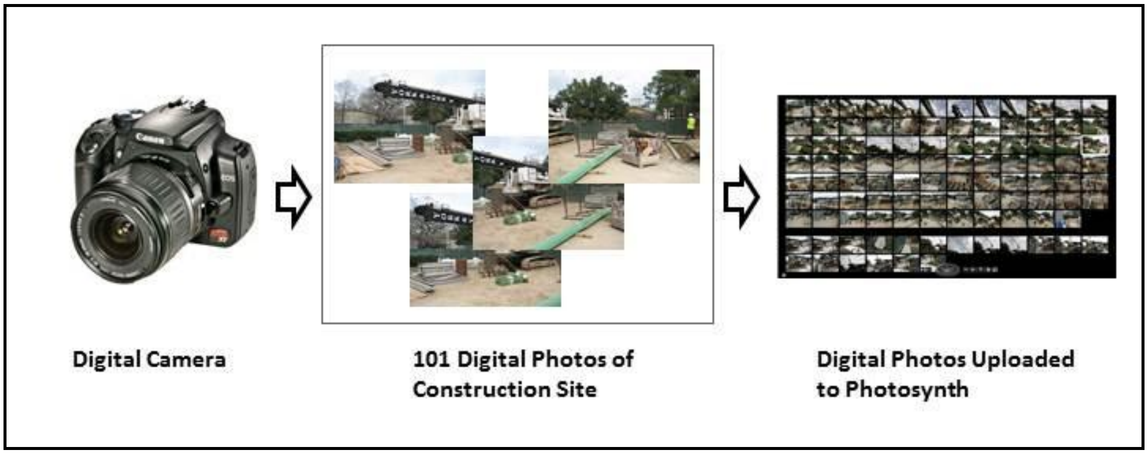
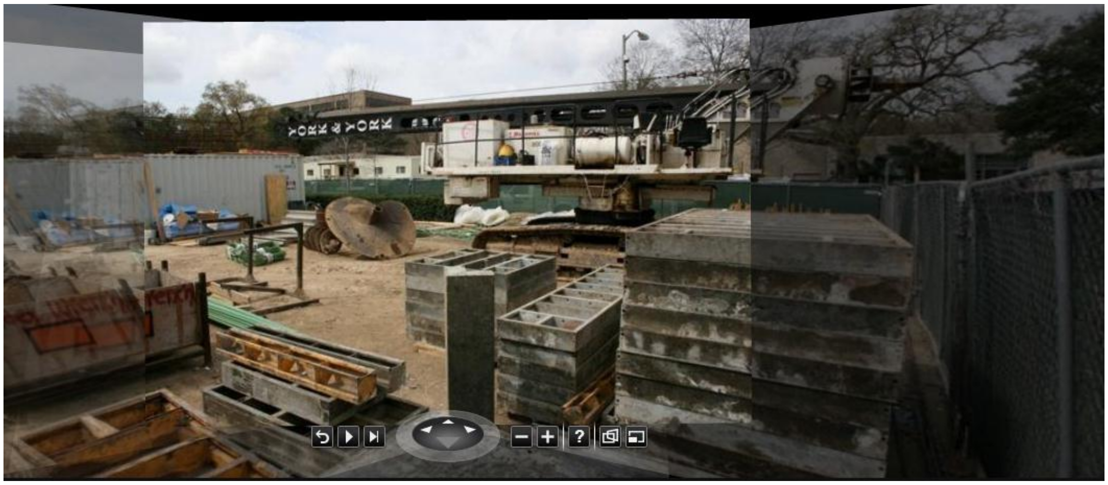


Figure 14 Capturing and uploading images to Photosynth

(a) Sample view 1



(b) Sample view 2

(c) Sample view 3

Figure 15 Sample views of stitched photos in Photosynth

As discussed in the previous section, for the space planning purpose, it is critical that the point cloud data hidden behind the panoramic view to be extracted for further modeling as shown in Figures 18 and 19. Although point-cloud data is available, Photosynth does not currently provide the service of exporting these data. Furthermore, SynthExport and Wire-shark, two potential tools for extracting point-cloud data from photosynth, were explored for the research. Our experiments showed that SynthExport takes less computational time and is more user friendly compared to Wireshark for extracting 3D point cloud from Photo-synth software. Wireshark requires many steps to derive necessary file formats. SynthExport is more integrated approach. Thus, an open source tool, SynthExport, was used for point-cloud data extraction (SynthExport 2010) as illustrated in Figure 17. This tool makes use of bin files which store point-cloud data located at Photosynth server and are later streamed to the local computer for visualization purpose. These locally created bin files are merged and converted to editable point-cloud data in several desired output formats, such as wrl, ply, obj and x3d. The choice of file format is dependent on the modeling software used in the subsequent steps. Thus, by using SynthExport, we extracted the 3D point cloud data from Photosynth in the form of ply, obj and X3D file formats. The next step is to import one of the file formats within 3D modeling software. Different possibilities were explored for the import of ply, obj and X3D files within Blender, which is 3D modeling software having the capacity of automatic surfacing. Our experiment shows that most suitable file format for surfacing is the ply file format, which used for this research. The next section describes automatic surfacing for 3D point-cloud model in details.

Figure 16 SynthExport window showing output formats

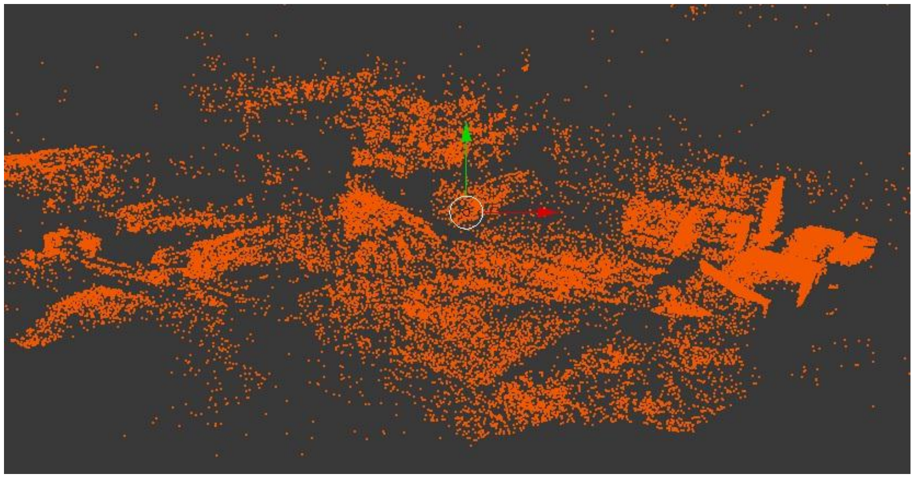
Figure 17 Photosynth window showing a top view and a camera location

Figure 18 Photosynth window showing the point cloud model

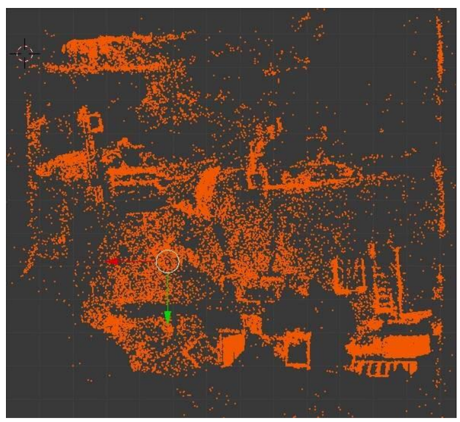
4.3 Step 3: Automatic Surfacing

The primary goal of this step is to use the point cloud skinner algorithm to automatically generate surfaces for the derived point-cloud data. Current work involves using Blender, an open-source 3D modeling tool, to model individual objects, and more work is under way to classify point clouds by clustering analysis first, so that the point cloud can be surfaced cluster-by-cluster (Point Cloud Skinner, 2007). Blender has options related to the use of free codes for solid modeling. Furthermore, the Blender package is an integrated system of software tools having capacity of solid modeling and animation of solids with high quality and complexity. It supports import and export of various types of files related to ply, 3DX and obj formats (Neves, Machado and Shiyou, 2011). Figure 20 (a) and (b) illustrates the raw 3D point cloud model imported to Blender. For the current case study, we used Ply format for the import of point cloud model into Blender. It is also available under double license and partially supports Python scripting. It is important to understand that solid objects are modeled by using Blender applications, while the export of boundaries and surfaces are achieved by Python. This format can be read by mesh generation program (Neves, Machado and Shiyou, 2011). Blender has been used for developing gaming applications and it has the capacity for animation and browsing different orthographic views which make it suitable for space planning.

Furthermore, current research is exploring the possibility of deriving 3D models which can be surfaced in order to achieve photorealistic visualization. Thus, from the research perspective use of Blender is important for future applications related to 3D model visualization and automation of mesh generation (Neves, Machado and Shiyou, 2011).



(a) Perspective View of 3D point cloud model

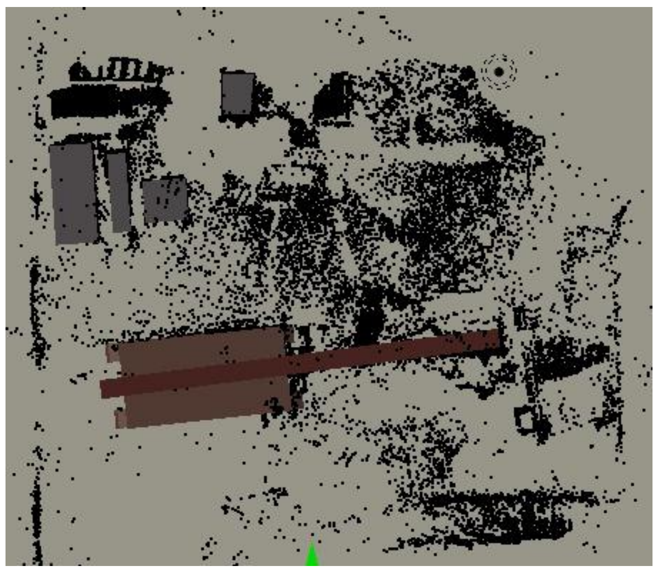


(b) Top View of 3D point model

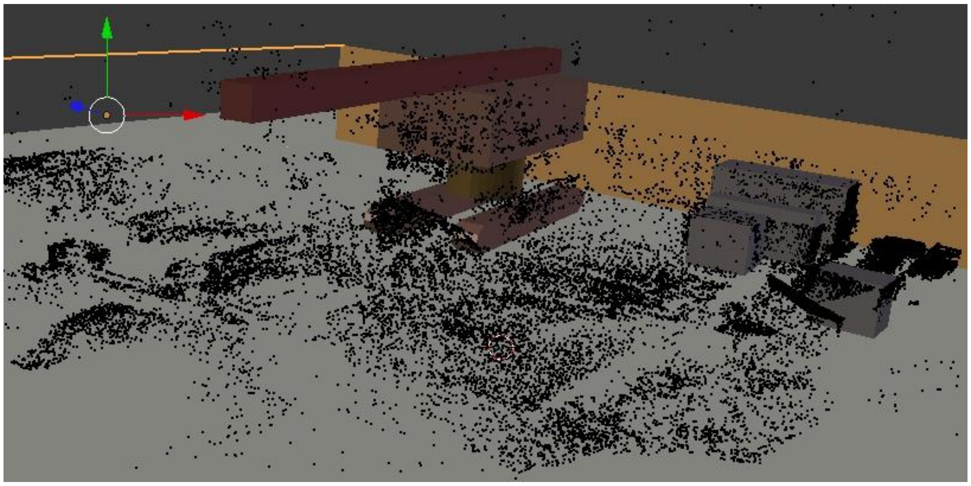
Figure 19 Views of extracted 3D point cloud model

4.4 Step 4: 3D Construction Space Modeling

The final step is to apply the derived 3D model for space planning. To demonstrate this application, we present a scenario in which space conflict is simulated by using existing conditions of the construction site, such as space constraints, material stacks, and temporary/permanent facilities. Figure 21 shows a 3D as-built model with reconstructed objects. The existing materials on site are colored in grey while planned material storages to be stacked are represented by yellow and blue colors, as shown in Figure 22. It is assumed that yellow materials are stacked on site after 10 days for 15 days and blue colored materials are stacked on site after 20 days according to the project schedule. It is observed that same site is being used repetitively for stacking of yellow and blue materials for 5 days which lead to a space conflict.

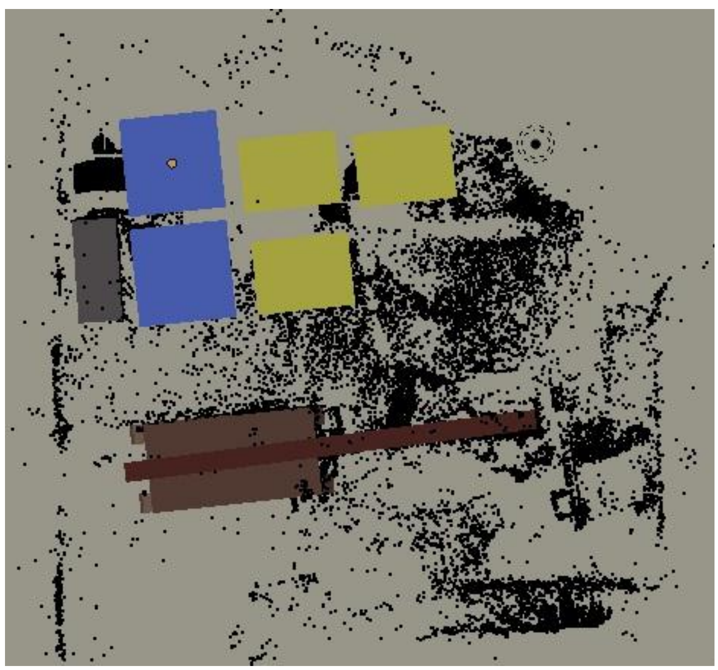


(a). Top view of the as-built 3D model

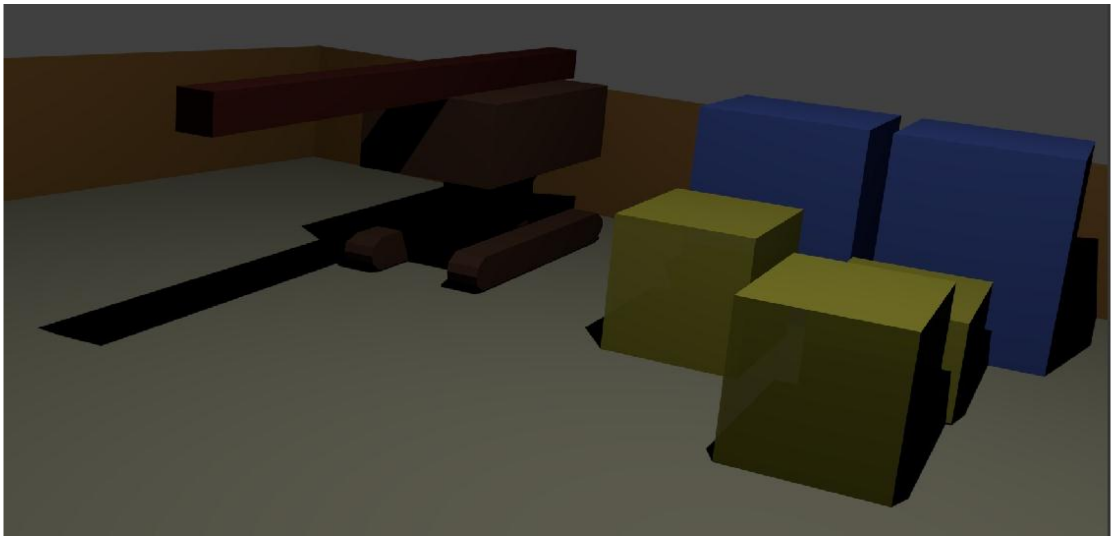


(b) Perspective view of the as-built 3D model

Figure 20 Views of the as-built 3D model



(a) Top view of the reconstructed scenario



(b) Perspective view of the reconstructed scenario

Figure 21 Views of the reconstructed scenario

Furthermore, this 3D model provides an overall idea of spaces around stacked materials. For example, if the crane needs to maneuver within the site, then materials need to be stacked in a way which will not only allow free movement of the crane horizontally but also of the boom. Thus, reconstructed 3D model not only provides a clear recognition of the future site conflict issues, but also helps in understanding the scenario from an intuitive 3D spatial perspective. This research proposes another possibility of linking a 3D modeling software with scheduling software. The main objective is to understand project scheduling with respect to space-time conflicts. Thus, a space-time conflict scenario is developed by using bar chart as shown in Figure 24. For demonstration purpose we consider three activities related to different material stacks on a given construction site. Although time conflict is evident from the bar chart, but the space conflict, i.e. stacking different materials on the same spot, is not immediately identifiable. This is because bar charts only carries one dimension of information, that is time, and using bar char itself will not characterize the usage of space. Thus, by combing bar chart schedules and 3D space visualization, efficient project scheduling can be achieved.

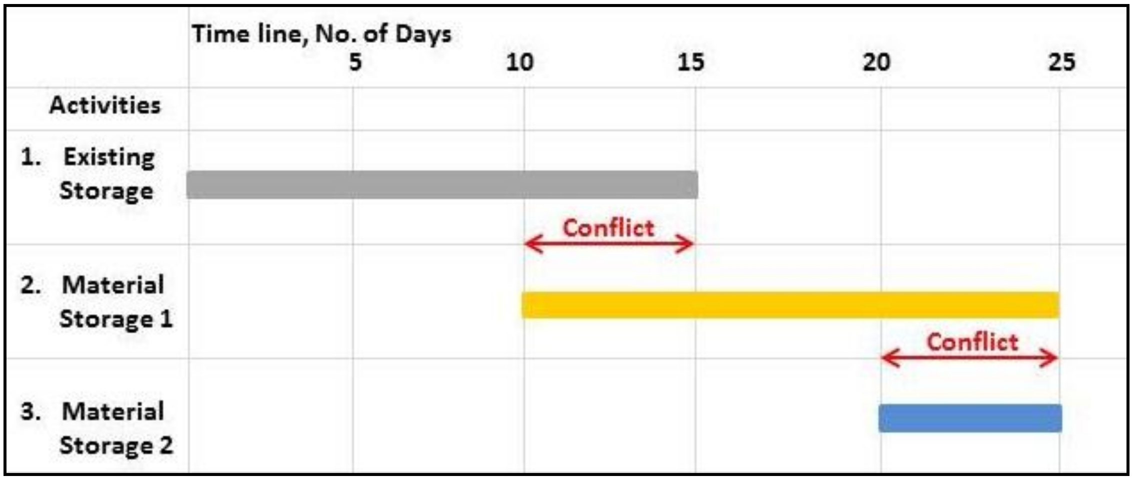


Figure 22 Bar chart showing space- time conflict

4.5 Lessons Learned

It is important to understand lessons learned in order to make efficient use of the proposed system. A strategy need to be devised earlier on in order to capture existing conditions of a construction site. The user needs to understand which objects to capture and how it could be captured efficiently. For example, we took detailed photographs of crane and material stacks from the construction site. This helped us to capture all major objects on a given construction site in detail. Another area which is also important is the quantity of images. In order to derive a greater percentage of matching, more overlapping images are required while capturing existing conditions. Guidelines mentioned in Chapter 3 can greatly help in the image capturing process. Furthermore, capturing some extra or back up images is highly recommended in order to derive 360° view of the construction site. This would help in getting better matching of the images later. If the first try of image stitching does not provide sufficient matching, then extra images would need to be added to achieve a better quality of image stitching. Outcome of other stages is highly dependent on the first stage of image stitching. Another area of importance is the file format of extracted point cloud. Choosing the appropriate file format for extracted 3D point cloud file is important in order to use 3D modeling software for automatic surfacing. In our case, ply file format was best suitable choice for the Blender software.

CHAPTER 5: CONCLUSION

This research is aimed at developing an automated photo-modeling based process to derive a 3D as-built model for construction site space planning. The photo-modeling concept helps to derive well defined point-cloud model of a construction site, which is then used for modeling basic objects in 3D modeling software.

An industrial case study validated practicality of the proposed technique for capturing as-built construction site conditions for space planning. The proposed system not only provides navigation within a 360° view of a construction site, but also allows exploring details of a particular area of a site. Furthermore, the data acquisition and processing process is efficient when compared with time required using laser sacnning. Another observation is related to the use of photo-modeling which helps to derive well defined edges of the objects that can be used to create virtual site models. These 3D virtual site models can help to make space planning, that is a 3D problem by nature, more effective. With the 3D models, it is easy to identify and understand the space conflict by recreating a scenario of the construction site environment. Finally, the open source software tools used in this research lower the cost of the prototype system and they also make future system integration possible.

Furthermore, it also supports the concept of using 3D visualization technique for understanding space conflicts and space planning. This research also validates the practicality of the process which could be used by any construction worker or an engineer on a personal computer. Thus, with the help of derived automation based system process, research objectives such as developing cost and time efficient process of capturing as-built site conditions can be achieved.

However, it should be noted that, like any photogrammetry-based method, the proposed approach will not work properly in the case of object occlusion, moving objects, and other noises, such as heavy traffic of equipment or workers on a given construction site. Finally, to fully automate the data capturing and modeling process, future work will integrate seamlessly the open-source components used in the current research.

Other future research can look into the area of integrating photo-modeling technique with other sensors for space planning. Augmented reality can be used to enhance the graphics and make virtual construction site environment even more realistic. A mobile hand held application can be developed on which 3D site model can be analyzed for space planning. Once fully implemented, this research will provide an efficient and cost-effective approach over traditional methods of space planning methods and 3D laser scanning.

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