Photo-modeling for Construction Site Space Planning

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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 for capturing as-built conditions for space planning purposes. This technique automates the reality-capturing process in which a series of 2D photos taken from different perspectives are used to derive an as-built 3D model of a construction site. The feasibility and effectiveness of the proposed approach is demonstrated in an industrial case study.

1. INTRODUCTION

Construction site conditions are dynamic in nature, involving numerous activities and resources scattered on a usually congested site. Safety risk and low productivity can usually be attributed to inefficient space planning and poor site logistics (Tawfik and Fernando, 2001). Thus, there is a strong need for accurately capturing the existing condition of a construction site for efficient and effective space planning. 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.

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). Laser scanning is a highly accurate technique for capturing as-built conditions based on the principles of range and time of flight. 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. However, laser scanning has several limitations in its use for space planning, where constantly changing site conditions must be captured frequently. The limitations include a large number of scans and require a considerable amount of time, high costs associated with the equipment, and the need for trained personnel to process the collected data (El-Omari and Moselhi, 2008). An alternative technique, photo-modeling, becomes attractive, mainly due to its lower cost and reasonable accuracy for capturing as-built conditions (Dai and Lu, 2010). Photo-modeling is a technique of extracting data in a form of point cloud from 2D photos and then mapping the data into a 3D geometrical space. 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). Recent development in photo-modeling focuses on not only its use for work progress measurement (El-Omari and Moselhi, 2008), but also construction safety management (Akinci and Anumba, 2008). This paper integrates the new development and techniques in photo-modeling to drive a 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 the 3D site model 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 a site traffic plan, conflict avoidance, and look-ahead scheduling. The following section describes related work in space planning and as-built modeling, which is followed by the proposed system. The practicality of the proposed process is demonstrated through an industrial case study.

2. LITERATURE REVIEW

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 have discussed space planning as an embedded task within construction planning and scheduling. Riley and Sanvido (1997) mentioned the importance of sequencing of various activities, their identification and potential spatial conflict resolution for efficient space planning. The authors also emphasized a greater need for preventing interference between crews, equipment, and stored materials. Traditionally, space planning is performed using 2D drawings. Waly and Thabet (2003) and Cheng and O' Connor (1996) 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 to develop 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). In short, past researches confirm the importance of space planning and the effectiveness of 3D virtual modeling technique over traditional methods for space planning. Different techniques based on photo-modeling in producing 3D as-built models are discussed below.

Photogrammetry was traditionally used as a technique for site surveying. During early days of photogrammetry, a special camera and equipment were required and photogrammetry was an entirely manual process. The transition from terrestrial photogrammetry to digital photogrammetry was due to the advancement of digital image capturing technology (Waldhausl, 1992). 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. El Omri and Moselhi (2008) discussed the advantages of photogrammetry-based approaches, such as the ability to acquire close range data and clarity in defining object edges. Golparvar-Fard et al. (2011) compared two point-cloud models, one generated by photogrammetry and one 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 does not add a burden on project management teams by requiring expertise for data collection or analysis as is the case of laser scanning. However, traditional photo-modeling does suffer some barriers related to the stitching of multiple 2D images to reconstruct a 3D model. In particular, in order to obtain a comprehensive view of a site, a large amount of acquired photos must be matched. This matching could be achieved by two means: 1) Use of artificial markers that must be applied to various locations of the site prior to photo shooting (Photo-modeler, 2011), and 2) Manual matching of the 2D images. Due to the significant effort required in both methods their applications to site planning were not practical. To automate the stitching process, Golparvar-Fard, Pena-Mora and Savarese (2009) focused on the reconstruction of a 3D model of a structure using geo-registered photos. It proposed a technique, Structure From Motion, to stitch images based on image feature detection and correspondence. Other research by Brilakis, Fathi and Rashidi (2011) focused mainly on the progressive 3D reconstruction of infrastructure using videogrammetry. This study also explains the advantages and disadvantages of various image capturing techniques, such as laser scanning, photogrammetry and videogrammetry. The authors also emphasized the requirement of minimum human intervention while processing the data and manual matching of 2D photos to derive a 3D model. In summary, past studies confirmed the efficiency and cost-effectiveness of the photo-modeling based technique when compared with 3D laser scanning. 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.

3. AUTOMATED 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 advancements in computer vision and 3D modeling techniques have made possible the automation of this reality-capturing and modeling process while minimizing human intervention. The presented procedure comprises of four steps as described in Figure 1 and detailed below.

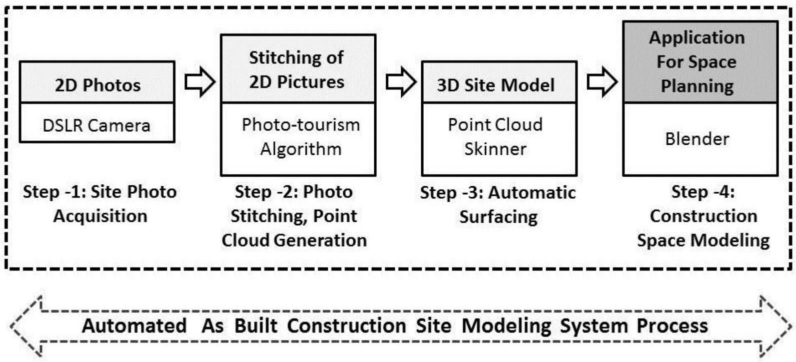

Figure 1. Overall Framework for Automatic As-built System Process.

3.1 First Step: Site photo acquisition

This step involves collecting images with overlapping features using a generic digital camera. In collecting the images, it is important to follow the "rule of three" in order to support the subsequent image matching step. This rule states that each part of a scene must appear in at least three separate photos taken from different angles. For better results, one needs an overlapping rate of more than 50% between subsequent photos. It is also desirable that photos be taken every 25° using a wide angle lens in order to capture a panoramic view of the scene. In addition, it is important to capture details and textures. Intermediate photos should be captured to record object details and their spatial relationship to other portions of the site.

3.2 Second Step: 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. 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).The stitching procedure involves the following process. First, Scale Invariant Feature Transform (SIFT) key-point detectors are used to identify feature points. This is necessary to transform image data into scale-invariant co-ordinates relative to local features in an image. SIFT features (e.g. corner points and edge lines) 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). The matches between each image pair are organized into tracks. A track 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 result is a common 3D co-ordinate system from images that have different camera parameters. Finally, the camera parameters and 3D positions are recovered by running an optimization algorithm to minimize the distance between matching key points and 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 planning of construction sites. In construction space planning, there is a need to acquire the geometrical data hidden behind the 3D photo views. Fortunately, while matching photos and generating the 3D 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 can be extracted and used to derive 3D models for construction sites. An alternative approach to Photo-tourism is Photofly developed by Autodesk (2011). 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 or have the capability of object editing and animation, which makes it unsuitable for this research. In addition, compared 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.

3.3 Third Step: Automatic Surfacing

This step involves automatic surfacing of the point cloud model derived from the step 2. It will provide end users a more realistic and intuitive 3D model of the site for space planning. 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. 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. 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 (Point Cloud Skinner, 2007).

3.4 Fourth Step: 3D Construction Space Modeling

This step involves the use of a 3D surfaced model for space planning purposes. As 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; for example, planned equipment and materials can be modeled as 3D objects or imported from other CAD modeling systems. With the 3D site 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. 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, the area surrounding an excavation pit represents a zone that 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.

4. CASE STUDY

A construction site located on The University of Houston main campus (Houston, Texas) was used as a case study to validate the above process. The project involved the expansion of the University's central plant. The expansion involves 8,000 sft at an estimated cost of $45 million. The following sections describe the four steps involved in the automation process as described above, as well as, lessons learned, and results. It should be noted that open source programs were used as much as possible in the development to provide opportunities for future system integration.

Step 1: Site photo acquisition

Over 100 Photos were taken of the jobsite using a Cannon Digital Single-Lens Reflex (DSLR) camera. As demonstrated in Figure 2, pictures were taken along the periphery of the site and important objects were documented by taking close-up pictures. More photos with overlapping features can also help in deriving a finer grained 3D point-cloud model.

Figure 2. Captured images

Figure 3. Sample of stitched photos

Step 2: Photo stitching and point cloud generation

The 2D images captured from the construction site were imported to the Photosynth web server (Microsoft Photosynth Network, 2011) from a personal computer. Figure 3 shows a portion of the resulting 3D photo view derived from matching of the images. The outcome of this step is a 360° view of the construction site which is navigable within Photosynth. As discussed in the previous section, it is critical that the point cloud data hidden behind the panoramic view to be extracted for further modeling. Although point-cloud data is available, Photosynth does not currently provide the service of exporting these data. Thus, an open source tool, SynthExport, was used for point-cloud data extraction (SynthExport 2010). This tool makes use of bin files which store point-cloud data located at the Photosynth server and are later streamed to a local computer for visualization purposes. 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. In this study, the ply file format was used to match our choice of modeling software that is described later. Figure 4a and 4b shows top view and perspective view of the raw extracted 3D point-cloud model of the construction site.

(a) Perspective View of 3D point cloud model. **(b)** Top View of 3D point model

Figure 4. Extracted 3D point cloud model

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 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.

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 5 shows 3D as-built model with reconstructed objects. As shown Figure 6, the existing materials on site are colored in gray while planned material storages to be stacked are represented by yellow and blue colors. 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 leads to a space conflict. 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 that will not only allow free movement of the crane horizontally but also of the boom. Thus, the 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.

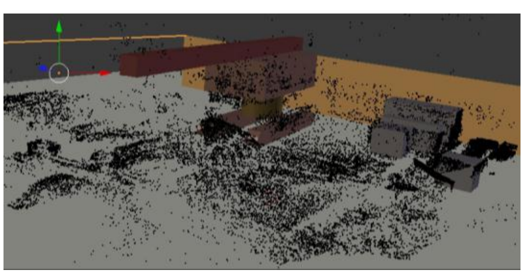

Fig 5. Perspective view of 3D point cloud and reconstructed objects.

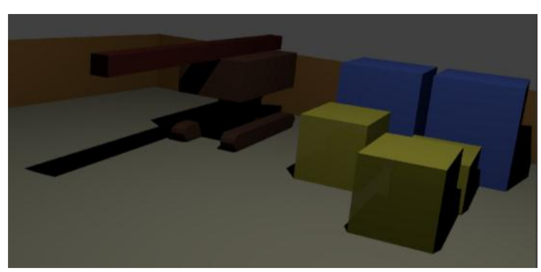

Fig 6. Reconstructed Scenario.

5. CONCLUSION

This research is aimed at developing and integrating various techniques to achieve an automated photo-based 3D modeling process for construction site space planning. The photo-modeling concept helps to derive a well-defined point-cloud model of a construction site, which is then used for modeling basic objects in 3D modeling software. A few open-source tools were used in our prototype system, which include PhotoSynth for photo stitching, SynthExport for exporting point cloud, and Blender for 3D modeling and surfacing. A case study validated the practicality of the proposed procedure, evidenced by the cost-effective data collection procedure, streamlined modeling process, and practical applications for space planning.

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. Furthermore, 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. However, the impact of occlusions and noises can be reduced or even eliminated by taking more photos that captures a scene from different viewpoints and avoids overlapping of objects. Meanwhile, photos should be shot during a relatively short period of time. This will help to reduce the chance of influence due to moving objects. Furthermore, noise reduction is also possible by taking photos when minimal activities are performed on a construction site and also by eliminating noise 3D points. Other future research might look into integrating photo-modeling techniques with other sensors for space planning. Augmented reality can be used to enhance graphics and make virtual construction site environments even more realistic. A mobile hand-held application can be developed on which a 3D site model can be analyzed for space planning right in the field. Finally, to fully automate the data capturing and modeling process, future work will integrate seamlessly the open-source components used in the current research. 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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