PHOTO-BASED 3D MODELING OF CONSTRUCTION RESOURCES FOR VISUALIZATION OF OPERATIONS SIMULATION: CASE OF MODELING A PRECAST FAÇADE

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ABSTRACT

3D models of building components or construction resources have been largely created by computer-aided-design (CAD) or by proprietary code for virtual reality development. Such 3D modeling methods entail accurate definition of points, lines and their relationships in the spatial coordinate system. Unlike CAD modeling, the surveying technique of photogrammetry takes a completely different approach by deriving metric information about an object through measurements conducted on photographs of the object. The very basic technique of photogrammetry is effective and computationally simple. With much less efforts, digital cameras and photogrammetry software have made possible 3D reconstruction of an object in digital form (coordinates and derived geometric elements). The resultant 3D models may well satisfy application needs in construction simulation visualization. In this paper, we introduce computing algorithms of photogrammetry and present an application of modeling a precast facade in 3D based on digital pictures taken at a building site.

1 INTRODUCTION

Three dimensional (3D) construction resource modeling incorporated with construction operations simulation can significantly enhance the credibility of simulation models (Kamat and Martinez 2001). Typically, construction researchers resort to computer-aided design (CAD) or proprietary code for virtual reality (VR) development to produce 3D models of construction resources (Kamat and Martinez 2001; Koo and Fischer 2000; Retik and Shapira 1999; Al-Hussein et al. 2006). Existing 3D modeling methods based on CAD / VR can achieve high geometric accuracy in representing points, lines and their spatial relationships. However, such methods tackle the 3D modeling of a new object from scratch, requiring manually sketching

the skeleton of the model. In general, much tedious and repetitive effort is demanded on the modeler and modeling procedures are time-consuming and inefficient. On the other hand, attaining high precision in 3D modeling, for most cases, is not a crucial issue for construction simulation visualization.

The photogrammetry methodology which originated in the surveying discipline provides a different approach of modeling 3D objects by deriving geometric information of an object directly from photos with proper perspective arrangement. By this modeling method, the outlines of objects can be automatically sketched in 3D computer graphics. At construction sites, it is normal practice that practitioners relies on the use of photos for documenting site records. In the past decade, the advent of digital cameras has largely removed the price tag on taking picture records to chronicle the evolution of a construction site. With site photos, a particular state of the site situation, including building products, construction resources and site layout, can be easily captured and kept. In an attempt to implement photo-based 3D modeling at a construction site, the reminder of this paper briefs the computing algorithm underlying photogrammetry, which provides the underpinning mathematical fundamentals. We then present a case study of modeling a precast façade at a building site so as to demonstrate the applicability of this modeling method under field constraints along with detailed modeling procedures.

2 PHOTO-BASED 3D MODELING

In order to enable the surveying technique of photogrammetry to extract data from two-dimensional images and map them onto a 3D object space, the mathematical equations called Collinearity Equations are established, which unifies the image coordinates system inside the camera with the corresponding object coordinates system in the

global space (McGlone 1989; Wong 1980; Wolf 1983). The Collinearity Equations mainly involve two aspects of orientations –namely, interior orientation and exterior orientation. The interior orientation describes the internal parameters of a camera within the image coordinates system in terms of the position of perspective center (O in Figure 1) projected to the image plane (x_o, y_o in Figure 1) and the distance between the perspective center and the image plane (c in Figure 1). The exterior orientation specifies six parameters of the camera in the global space, namely, the location *(Xo, Yo, Zo)* and the Euler orientation angles *(ω, ϕ, κ)* of the camera's perspective center. Figure 1 gives the pinhole camera model to illustrate how cameras normally form an image of an object. By applying the Collinearity equations, point coordinates can be bidirectionally derived within the two coordinates systems. Thus, any spatial points can be located by the intersection of two rays of light projected from two different camera stations.
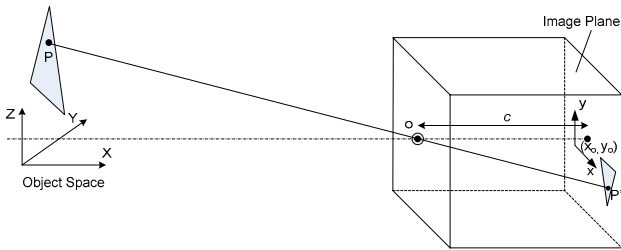

Figure 1: Pinhole camera model

Sketching out a 3D model by measurements performed on the photos has been applied in a variety of disciplines. With respect to applications in construction engineering and project management, Kim and Kano (2008) contrasted the site progress in the reality with in the plan by overlaying the photo-generated 3D site models with the as-planed VR scenes. Note, their research took fixed-point cameras for photo-taking, which means more than one camera was involved, and additional surveying apparatus was also used to determine the locations of those fixed-

point cameras and target points. Waugh (2006) employed construction site photos to implement a panorama view of the site situation for better site supervision, but this research didn't yield any 3D representation of site situations. To obtain the progress rate in complete percentage, a digitalizing construction monitoring model was devised aiming at monitoring the actual development of a construction project by extracting building components from site photos and further comparing them against volumetric 3D models plotted in AutoCAD (Memon et al. 2005). Nonetheless, the model was illustrated only with a simple case of box minifoundation, without sufficiently demonstrating the modeling capability with respect to handling more complex construction products or resources. In addition, contractors resorted to photogrammetry for 3D measurement of building geometries in order to preserve evidence documentation against potential construction-caused damage claims (Luhmann and Tecklenburg 2001). In general, literature and practice on implementing the photo-based 3D modeling in support of visualizing construction operations at site are still rare. To our best knowledge, in terms of visualization of construction operations simulation, modeling 3D site components by photogrammetry has not yet been attempted.

3   MODELING THE PRECAST FAÇADE ON SITE

3.1   Workflow Overview

In our research, experiments were conducted in modeling a precast facade at a building site as the first step towards the establishment of a photo-based 3D modeling approach in support of construction simulation visualization. Our field trials lead to generalization of the basic workflow of the modeling method, which consists of two phases, namely: on-site photographing and in-lab post processing of photos (Figure 2).

The phase of on-site photo taking is mainly concerned with acquiring adequate site photos, and these photos will provide input to later in-lab modeling. The on-site photo-
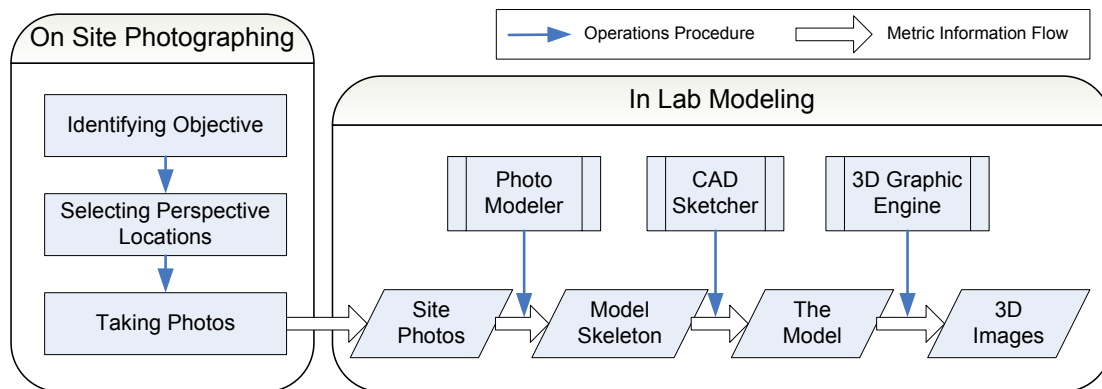

Figure 2: Basic workflow of photo-based modeling

graphing phase is composed of three steps: (1) identifying the object, (2) selecting perspective locations, and (3) taking photos.

In the phase of in-lab modeling, as shown in Figure 2, the site photos are imported from the digital camera into the personal workstation with photo modeler software in order to sketch out the model skeleton in 3D. The model skeleton depicts the basic geometry outline of the desired object but may not be as complete as desired, since data as of some edges or vertices of a complex object could be missing in those site pictures. Thus, the skeleton model will be further polished in a CAD environment (like Auto-CAD®, SketchUp®) before being finalized. The resulting skeleton model can then be rendered into realistic 3D object scenes for use in site situation visualization or operations simulation animation. Note rendering can be interpreted as the automatic process of converting 3D skeleton models (wireframes / surfaces) into 3D object images with photorealistic effects on a computer.

To materialize photogrammetry modeling in our experiments, we employed a well-established commercial software system – PhotoModeler® (Eos Systems Inc. 2007), which prevails both in the industrial markets and in the research fields. For finalizing the skeleton model, the AutoCAD® (Autodesk 2007) alongside SketchUp® (Google 2007) were used and compared in making quick embellishments on skeleton models.

3.2   Taking Photos on Site

A construction site differs from an ideal laboratory environment and presents numerous constraints on accessibility, line-of-sight, and lighting. Site constrains and limitations should also be taken into account in identifying site elements as meaningful modeling targets and fulfilling preset purposes. In this research, the modeling purpose is mainly to evaluate the feasibility of site photos based 3D modeling. A precast façade with relatively complex design features was the main production unit being handled in repetitive site operations at a residential building project in Hong Kong, thus lending itself well to simulation modeling and visualization. Additionally, the site conditions allowed us to place a camera at safe stations that could be conveniently accessed and presented no safety hazards when shooting pictures at site. Hence, a precast façade was selected in our case study. Figure 3 shows the frontal face of the facade with an alcove window.

Figure 3: The precast façade being modeled

When positioning camera stations, one rule for implementing photogrammetry is that the closer the angle between the light rays is to a right angle (90 degree), the smaller possible error will occur. In Figure 4 and 5, Station 1 has the same position and the same angle error, however, that placing Station 2 at an acute angle to Station 1 magnifies the small error, and thus the resulting position of the 3D point turns out much farther (Figure 5) in comparison with the result as shown in Figure 4.
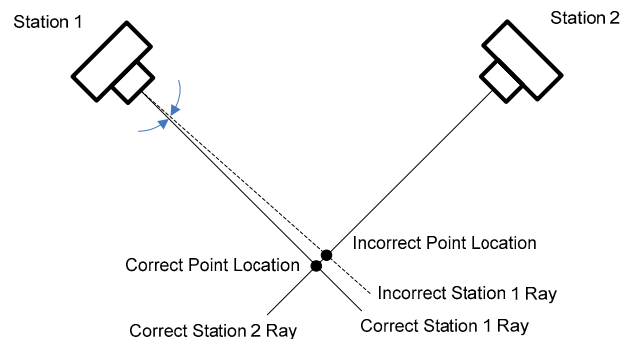

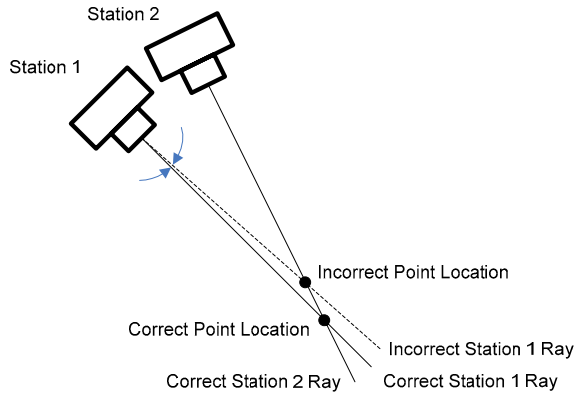Figure 4: Point location error with good camera positions

Figure 5: Point location error with bad camera positions

Figure 6: Camera station positions for a convex face
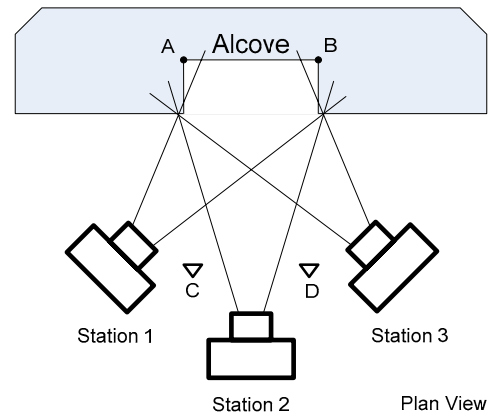
Figure 7: Camera station positions for an alcove

Theoretically, one point being covered in two photos is sufficient for fixing the point in 3D coordinates. But in practice, imprecision in point marking may cause another form of error. Point marking is the interaction process for identifying points explicitly on the photos to inform the modeling algorithm where the points' positions are. To alleviate this error, the desired point should be preferably covered on three or more photographs at the expense of redundancy. As such, if the point was positioned incorrectly on one of the photos, the other two could still compensate for the marking error.

To photograph a convex face of an object, normally three camera station positions would suffice. Figure 6 depicts the camera positioning layout. The camera stations are not at right angles to one another. Nonetheless, they are in proper positions to provide triple coverage of target points instead of double coverage. To photograph an alcove in an object usually requires more camera stations in comparison with photographing a convex face. Figure 7 shows the camera position layout for photographing an alcove object. In order to cover points A and B on three photographs respectively, extra station positions of C and D are recommended. The station C is inserted to ensure coverage for point B, while the station D targets at point A.

According to the above guidelines, to model the precast façade having relatively complex configuration basically requires 8 photos for covering the four convex faces and five for the alcove window in the frontal face.
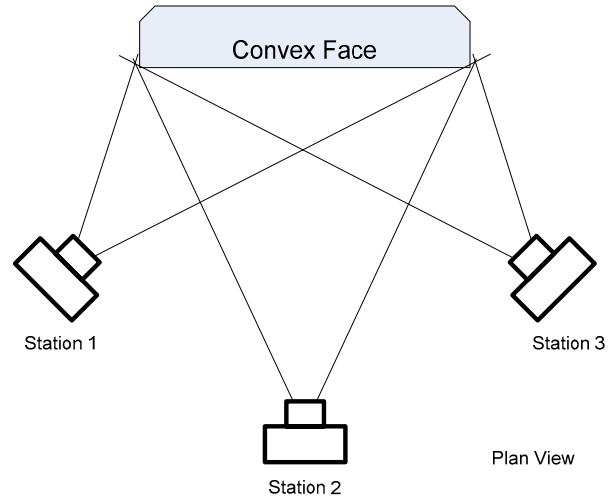
Still, not all the photos as required would be successfully acquired thanks to obstructions of line of sight by site elements and inaccessibility to some shooting stations at site. For this façade in case, the surrounding area at the rear face was relatively open while the frontal face was close to another facade laid in a row. This means there was limited room for placing the camera stations to photograph the frontal face as well as the alcove window at site. Instead of taking 13 photos as we originally planned, we managed to shoot 8 pictures.

Note, in many situations, it is impractical and expensive to repeat the photo-taking effort as justified to make up for low quality of certain photos, because the object in the original setting may no longer exist or its location or state have changed. Hence, it is advisable to take more-than-enough photographs of the object and choose to use only those as needed. As such, in case some of the photographs are unusable, or if more details want to be added, the modeler simply taps into the existing collection of photographs instead of revisiting the site and retaking photos.

By far, our experiments of testing cameras on real building sites have exposed several practical constraints. They are summarized as below:

- Obstacles getting in the way between the camera and the object. This may block the line of sight for certain feature points, causing loss of information in the photo. For example, edges or corners were cut in a photo by temporary supporting rigs.

- Lack of appropriate shooting perspectives, due in large part to the site being highly congested. For example, an inaccessible area did not allow us to place the camera; or the rear face of a tower being built could be photographed only at a inaccessible neighboring residential building.

- Tradeoff between shooting range and coverage detail. When taking pictures with a camera of fixed focal length (as required for photogrammetry analysis), photographers encounter the problem of how to resolve the tradeoff between staying far away from the object to capture a wide range of content and getting close up to grasp as many details of the object as possible.

Note, Figures 4 ~ 7 are adapted based on illustrations in PhotoModeler User's Manual (2004).

3.3   Calibrating the Camera

The camera used in this experiment was the off-the-shelf digital single lens reflection (DSLR) camera – Canon EOS 400D with the focal length set at 18 mm to obtain the widest shooting range of the camera. The camera calibration process is to determine the camera's interior parameters in terms of focal length, displacement of principal point, and distance between the lens and the image plane. As usual, there are two ways to decide on the camera parameter settings: (1) directly referencing the camera specification provided by the manufacturer and (2) conducting calibration procedures. Since conducting calibration on the camera gives higher accuracy to the final modeling, our experiment followed the calibration approach.

The calibration usually involves two steps: (1) taking the calibration photos, and (2) deriving the camera parameters with those photos. As Figure 8 shows, eight photos of a calibration grid are recommended to be taken from four edges of the grid with a combination of portrait orientation and landscape orientation. The calibration grid is a pattern of dots designed specifically for the Camera Calibrator in PhotoModeler®, and the Camera Calibrator is a computer program running on the algorithm for automation of the derivation of camera parameters. Since our experiment targeted for modeling site resources in support of visualizing construction operations, at the current stage, the research did not attach too much importance to modeling precision. As to the calibration outcome, the total error equaled 0.294, which satisfied the best requirement of a total error under 0.3 (PhotoModeler User's Manual 2004).

Note, calibration work is only needed in the first time of using the camera to take source photos. As long as the focal length doesn't change, successive modeling work can use the same calibration results to determine the internal camera parameters.
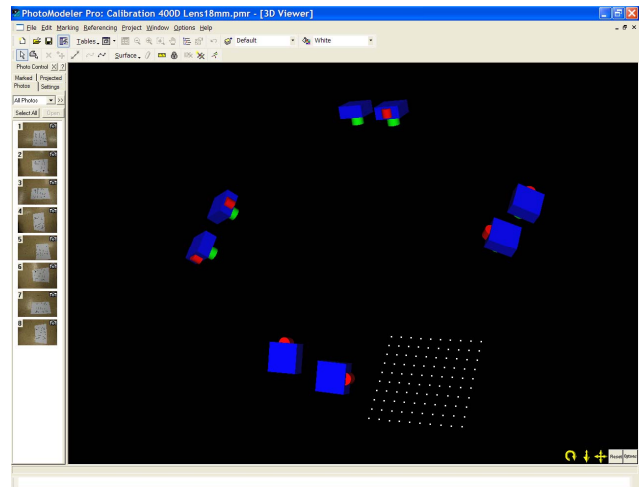

Figure 8: Eight camera locations derived in in PhotoModeler as part result of the camera calibration

3.4   Modeling with Photos

Modeling with photos in PhotoModeler mainly requires two kinds of human interactions– marking and referencing. *Marking* refers to using the mouse to identify vertices in the photos, and connect those vertices with edges. As shown in see Figure 9, the marked points are represented with cross dots, and the dashed lines connect those cross dots. The *referencing* work focuses on logically linking the same points in different photos. By highlighting the point in the source photo and selecting it in the destination photo, any points shown on both photos can be cross referenced. In Figure 9, both photos exhibit one side of the facade including the marked corners. Thus these corners can be referenced: e.g., the corner on the left bottom of the face (marked with red circles). Since the external orientation of the camera is described with six parameters, according to the Collinearity Equations, six points need to be referenced if coordinates of two camera positions are unknowns, and one point be referenced if working with one known camera station and one unknown camera station. After eight photos were marked and referenced, the eight cameras' locations and orientations were determined through computation and the skeleton model was automatically sketched as shown in Fig. 10.

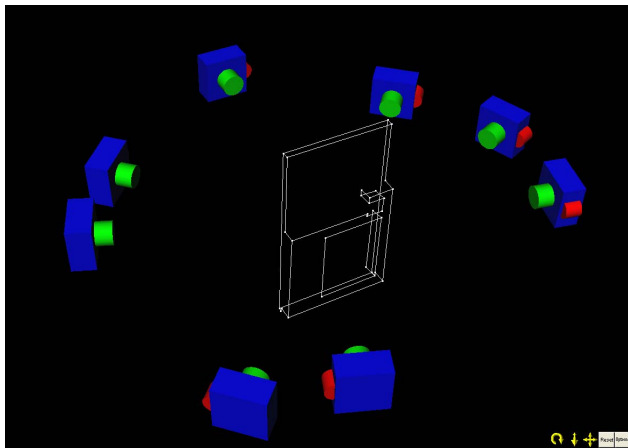Figure 9: Marking and Referencing the photos in Photo-Modeler

Figure 10: Eight derived cameras locations and the model skeleton of the precast facade

3.5   Completing the Model

The skeleton model produced from the PhotoModeler is incomplete with some vertices and edges being lost. In order to address such deficiency, our experiment further compared AutoCAD® and SketchUp® in embellishing the final 3D model. By comparison, AutoCAD® outperforms Google SketchUp® in terms of basic points snaps, auto lines alignment, and convenient lines offset, while SketchUp® enables automatic surfaces generation upon the wireframe model which is a prerequisite process for the later rendering operations. Accordingly, all missing verti-

ces and edges were fixed in AutoCAD® to transform the skeleton model into a wireframe model. The wireframe model can be regarded as a complete object representation by use of vertices and edges. These vertices and edges depict the outline of an object. Figure 11 shows the façade in final form of wireframe model conducted in AutoCAD®.
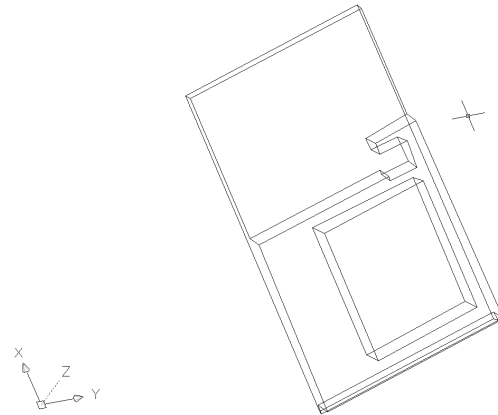

Figure 11: Wireframe model in AutoCAD®

Subsequently, SketchUp® was applied for editing the wireframe model into a surface model. The surface model represents the object in an ordered set of surfaces in 3D space, which makes the model amenable to better visualization and serves as the input for further 3D rendering by a graphic engine. In this wireframe model, polygon formed by vertices and edges does not ensure its coplanar configuration thanks to the errors induced during photo measurement processes. Meanwhile, 3D rendering by use of current 3D computer graphic engines only deals with a surface model composed of 3D triangular surfaces. Hence, surfaces in the surface model were represented by a triangular mesh in an effort to tailor the model to the requirements of computer graphics engines. This could be easily achieved in SketchUp® by slicing all polygons into triangular meshes, and SketchUp® is responsible for automatically attaching surfaces onto those triangular slicings. Figure 12 shows the 3D surface model of the façade.
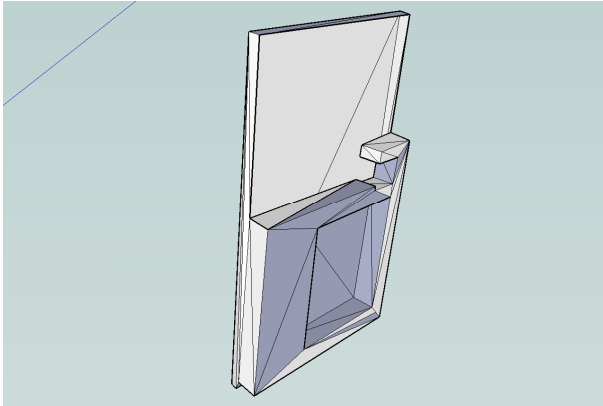
Figure 12: Surface model in Google SketchUp®

3.6   Modeling Results

At last, we chose the 4D-GCPSU (Four-Dimension Graphics for Construction Planning and Resource Utilization) as the visualization system to demonstrate 3D rendering effect. 4D-GCPSU was developed from previous in-house research, which enables a 4D model for visualizing a CPM construction plan in a 3D environment (Zhang et al. 2002a, 2002b; Wang et al. 2004). Figure 13 shows the rendering effects of the resultant 3D facade model, which proves to be acceptable and realistic for being incorporated into a 3D animation of the facade installation operations simulation.
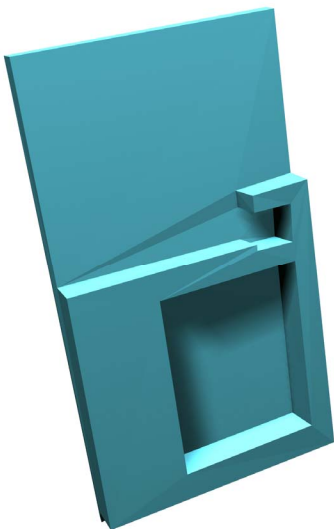

Figure 13: Rendering effects of the resultant 3D facade model in Tsinghua 4D-GCPSU

4   CONCLUSIONS AND FUTURE WORK

3D modeling of building components have been largely created by computer-aided-design (CAD) or by proprietary code for virtual reality development. In general, such 3D modeling methods entail accurate geometric definition but prove to be time-consuming and expensive. Unlike CAD modeling, the surveying technique of photogrammetry takes a completely different approach by deriving metric information about an object through measurements conducted on photographs of the object. With digital cameras, the photogrammetric measurement can be readily made through three dimensional reconstruction of an object in digital form. The resultant 3D models may well satisfy application needs in construction simulation visualization in 3D. This paper presents fundamentals of computing algorithms underneath photogrammetry. In a case study, we modeled a precast facade at a building site and found the resultant 3D facade model to be acceptable and realistic for being incorporated into a 3D animation of the facade installation operations simulation.

Future work involves more experimental modeling with regard to ongoing building structures and leading resources on site (such as the truck and the crane that handled the facade), so as to make this site photos based 3D modeling approach useful to generate prerequisite 3D models of construction resources for realistic, yet cost-effective visualization of operations simulation.

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