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Structure-From-Motion Approach to the Reconstruction of Surfaces for Earthwork Planning

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Abstract: The reconstruction of surfaces from unorganized point clouds can provide very useful information for construction managers. Although point clouds are generally created using 3D scanners, they can also be generated via the structure-from-motion technique using a sequence of images. Here we report a novel surface reconstruction technique for modeling and quantifying earthworks that can be used for preliminary planning, project updates and estimating of earthwork quantities, as well as embedded planning systems in construction equipment. The application of structure-from-motion techniques in earth works is examined and its advantages and limitations identified. Data from 23 earthwork excavation construction sites were collected and analyzed. 3D surface reconstructions during the construction phase were compared to the original land form. Similar experiments were conducted with piles of earth and the results analyzed to determine appropriate ranges of use for structure-from-motion surface reconstructions in earthwork applications. The technique was found to be most suited to pile of materials with volumes less than 2000 m^3. Piles up to 10 m in height and with base areas up to 300 m^2 were also successfully reconstructed. These results should be of interest to contractors seeking to utilize new technology to optimize operational efficiency.

Keywords: Structure-from-motion, construction, earthwork, image processing, 3D surface reconstruction

I. INTRODUCTION

Structure-From-Motion is a method for creating 3D models from 2D pictures of an object. The structure from motion approach to the reconstruction of surfaces from unorganized point clouds can be particularly useful in construction applications, satisfying high modeling and visualization demands. Monitoring the status of construction activity is important issue facing construction industry to keep timely knowledge of project status –where things are, what has been done, what needs to done [1]. A variety of metrology instruments like the robotic total station, RTK-DGP differential global position, fanning laser, LIDAR, LADAR, and real-time photogrammetry have been produced to facilitate the traditional earthworks associated in construction [2].

In this study, a surface reconstruction technique was utilized to model and quantify the types of earthwork typically found on construction sites. The resulting model is expected to provide a simple way for site engineers and planners, using the simplest instruments, to perform preliminary planning and to measure cut and fill volumes, or the volumes of material piles stored at or brought to the work site. This paper examines and provides a novel surface reconstruction technique for modeling and quantifying earthworks that can be used for preliminary planning, project updates, estimating of earthwork quantities, and equipment embedded planning. The paper also provides quantitative data on the accuracy of such techniques. Real actual data collected from different sites was collected and compared to data generated from the structure-from-motion technique. In addition, guidelines for applying the proposed technique are provided as an aid for application in the field.

II. BACKGROUND

A 3D imaging system is a non-contact measurement instrument used to produce a 3D representation (for example, a point cloud) of an object or a site [3]. A point cloud consists of a set of vertices in a three-dimensional coordinate system. These vertices are usually defined by X, Y, and Z-coordinates, and are typically intended to represent the external surface of an object. Point clouds are most often created by 3D scanners, which automatically measure a large number of points on the surface of an object and output this information in a data file, i.e., the point cloud. The point cloud thus represents the set of points that the device has measured. While point clouds can be directly rendered and inspected, the point clouds themselves are generally not directly usable in most 3D applications and are thus usually converted to polygonal triangle mesh models, NURBS surface models, or CAD models through a process referred to as surface reconstruction. There are many techniques for converting a point cloud to a 3D surface. Approaches such as Delaunay triangulation, alpha shapes and ball pivoting build a network of triangles over the existing vertices of the point cloud, while other approaches convert the point cloud into a volumetric distance field and reconstruct the implicit surface in order to define the shapes via the

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Marching cubes algorithm. Some examples of a 3D imaging systems are laser scanners (also known as LADARs [Laser Detection and Ranging] or LIDARs or laser radars), optical range cameras (also known as flash LIDARs or 3D range cameras), triangulation-based system such as those using pattern projectors or lasers, and other systems based on interferometry [3]. Common applications include surveying, volume determination, clash detection, creating as-built models, dimensional checking, tolerance checking, and topographic mapping [4],[5].

Models created using the data contained in point clouds can be used to construct an as-built building information model (BIM), which involves measuring the geometry and appearance of an existing facility and transforming those measurements into a high-level, semantically rich representation [6]. The process that must be followed to create an as-built BIM using laser scanners can be broken down into three main steps: 1) data collection, in which dense point measurements of the facility are collected using laser scans taken from key locations throughout the facility; 2) data preprocessing, in which the sets of point measurements (point clouds) from the collected scans are filtered to remove artifacts and combined into a single point cloud or surface representation in a common coordinate system; and 3) modeling the BIM, in which the low-level point cloud or surface representation is transformed into a semantically rich BIM. For as-built BIM applications, the data that makes up the point cloud is acquired using laser scanning technology. Laser scanners measure the distance from the sensor to nearby surfaces with an accuracy ranging from millimeters to centimeters, depending on the equipment specifications and project requirements. Since no single scanning location can visualize all the surfaces within a facility, a number of scans must be obtained from multiple locations in order to gain a complete representation of the structure [7],[8].

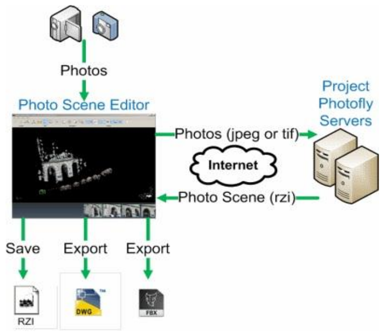
Another technique used for acquiring data for modeling is photogrammetry. A photogrammetric based model is applied to structural analysis by directly introducing 3D geometry files in the preprocessing module of computational software based on the Finite Element Method [9],[10],[11].In Armesto et al.'s study, the equipment used for recording and modeling consisted of an analog camera loaded with high resolution film, a scanner, a total station surveying tool and a digital photogrammetric station. When modeling construction work, it is often useful to integrate 3D laser scanning techniques with photogrammetry in order to enhance the 3D modeling process. This also overcomes some of the major limitations of 3D scanning, including the time required to perform a single scan (when using high angular resolution) and the number of scan-positions necessary to acquire accurate information [12], [13]. LIDAR scanning yields data in the form of point clouds which can be displayed as useful images using specialized software systems and these images can be viewed at different angles. Laser scanners can capture up to 2000 data points per second. However, although automated photogrammetric matching algorithms can produce very dense point clouds, mismatches, irrelevant points and missing parts may be present in the results and it is therefore important to perform a post-processing check of the data.

Along with the improvements of 3D imaging systems 3D imaging systems used for construction applications increasingly match the industry requirements for faster data acquisition, more accurate measurements, increased resolution, and reduced size or increased portability. Other benefits of site scanning are the real assessment of construction process, remote monitoring, early detection of errors, and improvement of project planning and documentation. However, the use of 3D imaging systems, such as LIDARs and LADARs, requires substantial capital investments due to the high costs of instruments and the software with well-trained personnel for both hardware and software. In general, scans need to obtain from several locations to capture the scene fully and eliminate occluded objects and features. Multiple location scans are time consuming process for the setup of instruments. Additionally, interoperability between software packages and between software and hardware packages are the most important needed for the future development.

The growing demand for better modeling and visualization of existing shapes and surfaces, along with the increased awareness of the high information density a single digital photograph can contain; has motivated a great deal of research in the field of surface reconstruction from digital photos. For example, Microsoft Live Labs (now part of Bing) and the University of Washington jointly developed “Photosynth”, (now called 123D Catch) a software application that analyzes digital photographs and then generates a three-dimensional model and a point cloud of the object photographed. The software company Autodesk took a different approach: their Project Photofly offers a technology preview that automatically converts photographs shot around an object or of a particular scene into "Photo Scenes" by utilizing the power of cloud computing. To achieve this, a standalone application for Windows called “Photo Scene Editor” has been developed that enables the user to submit photographs to the Project Photofly web service and then view the returned Photo Scenes. The user can save Photo Scenes, and export the computed 3D points, cameras and geometry in various CAD formats. While Microsoft Photosynth is designed as an image browser for objects documented by internet imagery [14], Autodesk technology enables the user to save the generated model to his or her disk for further processing and analysis.

Although using photographs as the data source may not always be the most accurate technique, it is often the most convenient recording mode on site. The equipment involved is easy to handle and simple to transport, neither of which is the case if a laser scanning device must be used. The remainder of this paper will show how this technology can be used for earthwork applications on construction sites and discusses the pros and cons of adopting this approach. The application of structure-from-motion techniques presented in this paper utilizes a digital camera with free software to capture 23 earthwork sites and processes the image date into a 3D model of an object. This approach is cost-effective and quick conducive 3D reconstruction method to monitor the status of construction activity.

III. OVERVIEW OF PROJECT PHOTOFLY



(a)

(b)

FIGURE I
(a) HOW PHOTOFLY WORKS
(b) THE PHOTO SCENE EDITOR INTERFACE

Project Photofly consists of two main components: its Camera Factory engines, which run in the cloud, and Photo Scene Editor, which is a Windows-based client application (Fig. 1).

IV. PHOTO SCENE CREATION WORKFLOW

The creation of photo scene starts from the establishment of the right images in the field. This requires users to capture a sufficient number of pictures of the object from the right angles and positions. The following shoot guidelines are of the important steps to take the right images.

- Any standard digital camera can be used as long as it has a reasonably high resolution (5 million to 10 million pixels).
- There must be significant **overlap** between adjacent Source Photos.
- Each Source Photo must contain both **foreground** and **background** portions of the scene.
- Each area that is to be turned into a 3D point must be seen from **at least 3 camera angles**.
- Shoot pictures every 10° (roughly) around the scene or object to ensure sufficient overlap between adjacent viewpoints.
- Make sure the most important scene content is recorded from multiple viewpoints.
- Minimize zoom to capture the widest possible images, and retain the same settings for the entire scene.
- Preferably shoot close-ups from close to the target rather than by zooming.
- Identify clear areas that will be used to set the scale and reference coordinate system.
- Measure a reference distance.

After the shooting of right images, the steps typically involved in creating a photo scene are as follows:

1) Create a photo scene. This step requires that users select the photographs to be included in the scene and then use the PSE to process them to create the scene and the corresponding point cloud.
2) Edit the photo scene. PSE enables users to view the 3D cameras and Automatic Point Cloud either in 3D space or through each camera. Users can add reference points, some reference lines and define a coordinate system at this stage.
3) Export the Photo Scene. Once the processing is completed to the user's satisfaction, they can export the edited scene in different file formats and to different software, depending on their requirements.

V. EARTHWORK APPLICATIONS USING IMAGE BASED 3D MODELING

Image based 3D modeling can be particularly useful for executing and planning earthwork projects. For this study, Autodesk’s technology was applied to two vital applications typical of those utilized in earthwork projects: Earthwork Topographic Modeling and quantities monitoring and calculation.

A. Earthwork Topographic Modeling

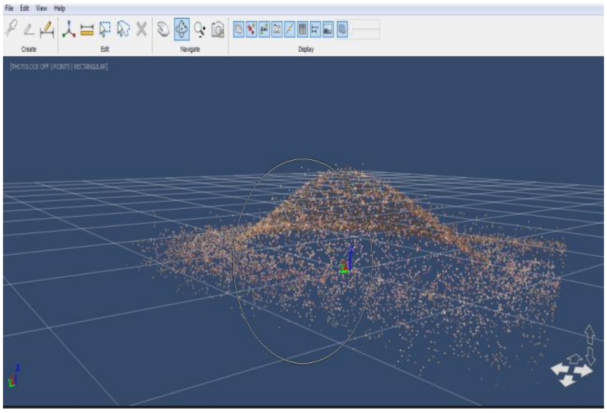
Topography modeling is considered a basic and very important step for earthwork planning. Various tools are available for topography modeling, ranging from conventional survey techniques to the use of software such as Google Earth. The three major factors determining the optimum tool for a given situation are: 1) the accuracy required; 2) the time available; and 3) the cost. Although not capable of delivering the most accurate results, both the time needed and the cost incurred by implementing image based 3D modeling for earthwork purposes compare favorably to those for other approaches. In trials of several practical earthwork modeling applications conducted for this study, the only instruments needed were a standard digital camera (in this case a Sony DSC-P150 with a resolution of 7 megapixels was used), the latest version of Photo Scene Editor, and an internet connection.

B. Quantities monitoring and calculation

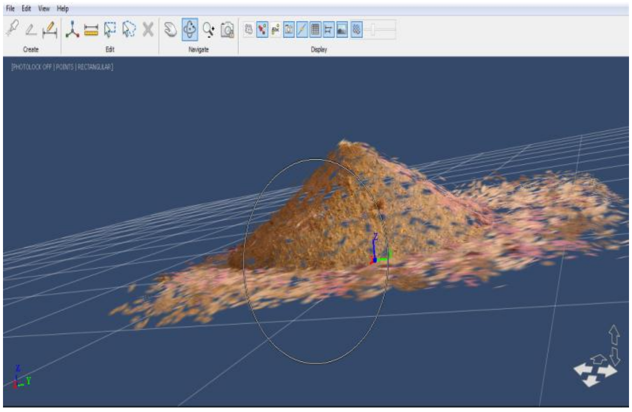
The second application image based 3D modeling technique involved measuring and monitoring earthwork quantities on site. Applying such techniques can make the process of measuring the quantities of soil brought on or off a site more robust. It also enables project managers to track the work done on site on a daily basis. Here, a series of photos were captured showing the material to be measured, whether in the form of piles stored or holes dug in the work site. These photos were then modeled through PSE and the output point cloud exported to Autodesk Civil 3D for conversion into a surface. Auto desk Civil 3D offers several tools that can be used in modifying and analyzing surfaces. Using these tools, the volume of the modeled surface was calculated.

The specific case study for this approach was a test pile taken from a refill sand pile stored on a construction site. The sample was taken using a 930H Caterpillar Wheel Loader with a 2.5 m^3 bucket capacity. Two full bucket loads were taken and piled away from the original stored refill soil. Using a pre-determined bucket load made it possible to determine the exact volume of the sample for comparison with the volume calculated using the new image based 3D modeling technique. Based on the size of the bucket used, the actual volume of the sampled sand was 5m^3.

The modeling process began by capturing a series of digital photographs. The 47 images captured were uploaded to PSE to create the scene, a process which took 7 minutes. After creating the scene (Fig.2), this was exported as two file formats, a DWG file and an LAS file, to start modeling the extracted point cloud. The two exported files were then used by the software package Civil 3D to create a surface from the resulting point cloud. The steps followed to create the surface are as follows: first the DWG file is opened using Civil 3D. At this stage, only a blank screen is displayed. To view the extracted point cloud, a link and index file to the DWG file is needed, which in this case is the LAS file. After creating the point cloud file and attaching it to the opened drawing, the user must specify additional data, namely the insertion point coordinates, the point cloud scale and the rotation angle, if any. This enables the process of importing the point cloud into Civil 3D to be completed, after which the next step is to model this point cloud to a surface (Fig 3). To do this, civil 3D properties must be added to the created point cloud by selecting the Add Civil 3D properties option on the main toolbar. This converts a primitive point cloud to an AutoCAD Civil 3D point cloud.



(a)



(b)

FIGURE II
(a) SAMPLE SAND PILE POINT CLOUD
(b) SAMPLE SAND PILE CREATED SCENE

AutoCAD Civil 3D point clouds have some distinct characteristics compared to AutoCAD or other AutoCAD-based applications such as AutoCAD Map 3D. The main difference is how the point cloud objects are stylized and displayed in the drawing. For example, an AutoCAD point cloud object is displayed with the properties of the layer where it resides, whereas AutoCAD Civil 3D and AutoCAD Map 3D point clouds are generally displayed using the LiDAR point classification scheme. Another important difference between AutoCAD and AutoCAD Civil 3D point cloud objects is the ability of the latter to recognize coordinate system information related to the source data and transform it when the point cloud database is created.

Once Civil 3D properties have been added to the point cloud, the user can then add these points to a surface, a process known as surface reconstruction. Civil 3D facilitates this process by providing a tool for users to add extra point cloud object points to existing surfaces or to create new TIN surfaces. By selecting the desired point cloud, the option Add points to surface appears in the main tool bar. Before adding these points to the surface, the software prompts the user to select whether these should be added to a new or an existing surface. Users can choose a style for the surface that will be created and, most importantly, specify whether the whole set of points will be added to the surface or only a portion of it. This latter point is critical, as the imported point cloud is likely to contain undesired parts or points, depending on the application. Selecting the relevant portion of the point cloud is the final step in the surface reconstruction process, after which the pile to be modeled has been converted into a surface (Fig. 4).

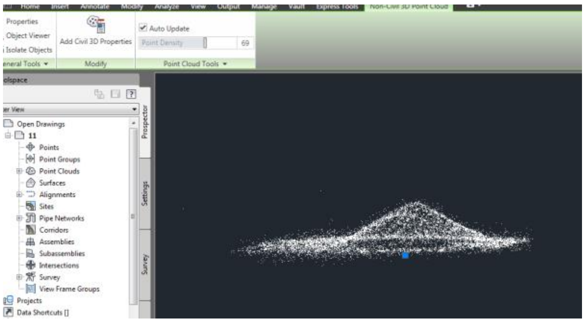


FIGURE III
A POINT CLOUD IN CIVIL 3D

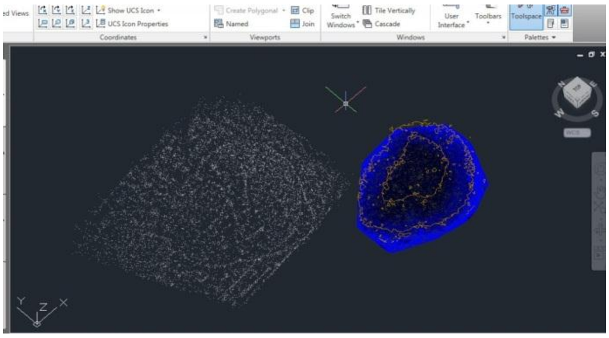


FIGURE IV
A POINT CLOUD AND ITS CORRESPONDING RECONSTRUCTED SURFACE

Once a Civil 3D surface has been constructed, a wide range of analyses, modifications and calculations can be performed. For quantities monitoring and calculations, the important feature is likely to be the volume calculation. In Civil 3D, volumes are calculated using the composite method, which triangulates a new surface based on points from two surfaces. This method uses the points from both surfaces, as well as any location where the edges of the triangles between the two surfaces intersect, to create prismoidal segments from the composite TIN lines. The new composite surface elevations are calculated based on the difference between the elevations of the two surfaces, as shown in Fig. 5.

The modeled surface is considered to be the comparison surface and a flat surface is created to act as the base surface. The base surface should have the same perimeter as the comparison surface in order to obtain the most accurate volume. In the case of the sand pile used in this study, the modeled surface volume was found to be 4.83 m^3, with a consequent error of 0.17 m^3, or 3.4%.

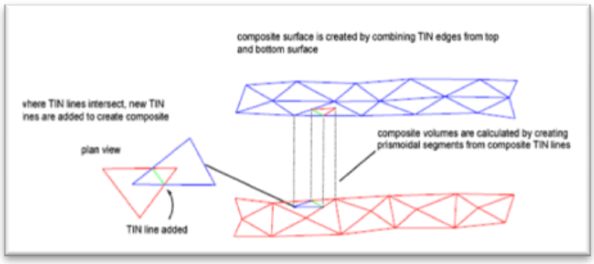


FIGURE V
COMPOSITE SURFACE ELEVATIONS CALCULATION TECHNIQUE

VI. MODEL ACCURACY TESTING

The three primary factors limiting the accuracy achievable using this approach are: 1) the soil type, 2) the number of photographs used to model the surface, and 3) the actual volume of the surface to be modeled. The effect of the soil type on the modeled surface volume was tested by modeling four different samples composed of different soil types. Piles from 23 different sites were collected (6 were refill sand, 6 were gravel, 6 were excavated sand and 5 were crushed stone). The actual volumes of the piles used were based on the volume of the truck loads of materials removed from sites and dumped in the piles. The volume of the 23 piles ranged from 800 m^3 to around 2000 m^3. In addition the pile heights ranged from 3 meters to 10 meters with base areas from 50 m^2 to 300 m^2. The permutations of pile volume, height, material type, and base area were made to allow to test the different parameters are explained next.

TABLE I
EFFECT OF CHANGING THE SOIL TYPE ON THE ACCURACY OF THE MODELING TECHNIQUE

Soil type	Number of photos	Actual volume (in 100 m^3)	Model volume (in 100 m^3)	% error
Refill sand	50	7.5	7.26	3.20
Gravel	50	7.5	7.87	4.90
Excavated sand	50	7.5	7.76	3.50
Crushed stone (dolomite)	50	7.5	7.94	5.90

All four samples had the same volume and for each the same number of images was used as the PSE input. Table 1 shows the % error for each soil type. These results indicate that the error increases when the soil granularity increases, which may be due to the fact that the more granular the soil sample, the noisier and spikier the corresponding modeled surface becomes.

TABLE II
EFFECT OF CHANGING THE NUMBER OF IMAGES CAPTURED ON THE ACCURACY OF THE MODELING TECHNIQUE

Soil type	Number of photos	Actual volume (in 100 m^3)	Model volume (in 100 m^3)	% error
Refill sand	30	5	4.21	15.80
Refill sand	40	5	4.64	7.20
Refill sand	50	5	5.19	3.80
Refill sand	60	5	5.17	3.40
Refill sand	70	5	5.1705	3.41

The second factor considered was the number of photographs used as the PSE input. Table 2 presents the effect of changing the numbers of photos on the model accuracy, with both the material and volume remaining constant. The table shows that increasing the number of captured photos does indeed increase the model accuracy due to the increased point cloud density obtained. However, this effect becomes steadily less significant with increasing number of images; above 60 images no improvement in accuracy is observed.

The final factor tested was the effect of the actual pile volume on the model accuracy. Table 3 shows how the model accuracy changed with changing pile volume. Here, the material and number of images remained the same. The results show that increasing the pile volume had no significant effect on the model accuracy. This may be due to two reasons. First, increasing the pile volume means its shape became more defined and it could thus be more easily distinguished from its surroundings. Second, the error is calculated by finding the difference between the actual and the model volumes then dividing the result by the actual volume. Hence, the increase in the numerator, which represents the difference between the actual and the model volumes, remains relatively small compared to the denominator (i.e., the actual volume) for all these cases.

TABLE III
EFFECT OF CHANGING THE PILE VOLUME ON THE ACCURACY OF THE MODELING TECHNIQUE

Soil type	Number of photos	Actual volume (in 100 m^3)	Model volume (in 100 m^3)	% error
Refill sand	50	5	4.82	3.60
Refill sand	50	7.5	7.24	3.47
Refill sand	50	10	10.34	3.40
Refill sand	50	12	12.46	3.83
Refill sand	50	20	20.73	3.65

VII. CONCLUSION

The work presented in this paper demonstrates the applicability of the structure-from-motion technique for earthwork quantity determination commonly found on construction sites. The approach utilizes surface reconstruction techniques to support general practices such as preliminary planning and measuring cut and fill volumes. Structure-from-motion techniques applied to earthworks were used to validate a 3D surface reconstruction approach and the results tested in 23 excavation construction sites to reveal the new technique's limitations, along with its advantages and disadvantages. Three factors that could affect the accuracy of the developed model were identified, namely the soil type, number of images used to model the surface, and the actual volume of the surface to be modeled. The effect of each of these factors on the accuracy of the model was measured and found to be below 5% in almost all the cases tested. These results confirmed that the model is credible and this approach offers a useful tool for contractors seeking to improve their operational efficiency by improving their materials estimation capabilities through the routine use of this technology. There are a few limitations to the approach proposed here. Firstly, the size of the excavation must not exceed range the camera is about to capture with an appropriate resolution. Secondly, there must be enough and accessible vantage points around the site to capture enough photographs for the technique to work. Thirdly, weather and lighting conditions may affect the accuracy of the model.

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