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# STRUCTURE-FROM-MOTION FOR EARTHWORK PLANNING

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**ABSTRACT:** The reconstruction of surfaces from unorganized point clouds can be of great use in construction applications. Point clouds are mostly created by 3D scanners. Another technique for generating point clouds is the structure-from-motion technique, where the point cloud is generated from a sequence of images. This paper utilizes a surface reconstruction technique to model and quantify earthwork. The described technique can be used in preliminary planning, for project updates, estimating of earthwork quantities, as well as for embedded planning systems in construction equipment. The paper examines the use of structure-from-motion techniques in earthwork application and identifies limitations and, pros, and cons of this approach. Data from 23 earthwork excavation construction sites were collected and analyzed. 3D surface reconstructions were applied on the 23 sites during the construction phases and 3D surfaces were reconstructed and compared to the original land form. In addition, similar experiments were conducted with piles of earth. The results were analyzed to determine appropriate ranges of use for structure-from-motion surface reconstructions in earthwork applications. Results show that the technique is most suited for pit excavations with areas less than 2000 meter squared and with depths up to 5 meters. In addition, piles up to 10 meter highs and with base areas up to 300 meters were successfully reconstructed. The results of this paper should be of great importance to contractors willing to utilize this technology in everyday use.

**Keywords:** *Structure-from-motion, Construction, Earthwork, Image Processing, 3D Surface Reconstruction*

## 1. INTRODUCTION

The reconstruction of surfaces from unorganized point clouds can be of great use in construction applications, and it can satisfy high modeling and visualization demands. A point cloud is a set of vertices in a three-dimensional coordinate system. These vertices are usually defined by X, Y, and Z coordinates and typically are intended to be representative to the external surface of an object. The point cloud represents the set of points that the device has measured.

While point clouds can be directly rendered and inspected, usually point clouds themselves are generally not directly usable in most 3D applications, and therefore are usually converted to polygonal triangle mesh models, NURBS surface models, or CAD models through a process commonly referred to as surface

reconstruction. There are many techniques for converting a point cloud to a 3D surface. Some approaches, including 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 through Marching cubes algorithm.

Containing such important data, a point cloud can be used in several applications or in other words, the model created from a point cloud can be used in several applications. Models created from point clouds can be used in the creation of an as-built BIM, a process involves measuring the geometry and appearance of an existing facility and transforming those measurements into a high-level, semantically rich representation [1].

Creating an as-built BIM using laser scanners can be divided 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 the as built BIM application, the technology used in acquiring data (i.e., point cloud) is Laser scanning technology. Laser scanners measure the distance from the sensor to nearby surfaces with millimeter to centimeter accuracy, and since no single scanning location can visualize all surfaces within a facility, scans must be obtained from multiple locations.

Another technique for acquiring data for modeling is photogrammetry. A photogrammetric based model was applied to structural analysis by directly introducing 3D geometry files in the preprocessing module of computational software based on the Finite Element Method [2]. The equipment used for recording and modeling was 1) Analog semi-metric camera, Rollei 6006, 2) A Kodak Professional Ektachrome E100SW, 3) ScannerHPSCANJET7400C, 4) Laser total station Leica TCR 307, and 5) Photomodeler Pro 5.0, monoscopic digital photogrammetric station.

Another approach to model construction work was to integrate 3D laser scanning technique with photogrammetry to enhance the 3D modeling process and overcome 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 [3]. The LADAR scanning - which represents the 3D scanning tool - yields data in the form of 3D points, or "point clouds" which are later displayed as useful images using specialized software systems. These images can be viewed at different angles. Laser scanners can capture up to 2000 data points per second.

Automated photogrammetric matching algorithms can produce very dense point clouds, but mismatches, irrelevant points and missing parts could be present in the results, requiring a post-processing check of the data.

In this paper a surface reconstruction technique is utilized to model and quantify earthwork, it is intended to simplify for site engineers and planners, with using the simplest instruments, preliminary planning or measuring cut and fill volumes, or the volumes of material piles that is stored or brought to work site.

The growing demand in modeling and visualization of existing shapes and surfaces, and the awareness of the high information density a digital photograph can contain; motivated the research in the field of surface reconstruction from digital photos. Microsoft live labs and the University of Washington jointly developed "*Photosynth*", a software application that analyzes digital photographs and generates a three-dimensional model of the photos and a point cloud of a photographed object. Autodesk, on the other hand, worked on the "*Project Photofly*", which is a technology preview that automatically converts photographs shot around an object or of a scene into "Photo Scenes" utilizing the power of cloud computing. To use the power of Photofly, a standalone application for Windows called "Photo Scene Editor" has been developed. This application enables the user to submit photographs to the Project Photofly web service and 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 [4], Autodesk technology enables the user to save the generated model to his disk for further processing and analysis.

Using photographs as the data source, although is not the most accurate technique, but it is the most convenient recording mode on site. The equipment used in this technique is easy to handle and its transportation is in no case a problem as it can occur if a laser scanning device has to be used.

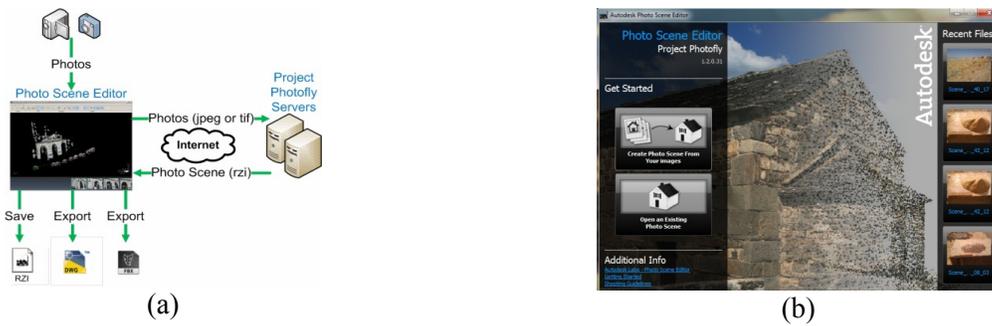


Fig. 1: (a) How Photofly Works and (b) Photo Scene Editor Interface

The following part of this paper will show how Autodesk's technology in earthwork application was utilized and what are the cons and the pros of this approach.

## 2. OVERVIEW OF PROJECT PHOTOFLY

Project Photofly includes a) Camera Factory engines that run in the cloud, and b) The Photo Scene Editor, which is a Windows-based client application.

The link between the user and Autodesk labs server, where photos converted into 3D models and point clouds, is the Photo Scene Editor. The Photo Scene Editor is a Windows-based application that lets you submit your images to the Project Photofly server, to automatically run the Stitching process, and to view the Photo Scenes returned by the server. Using the Photo Scene Editor, you can edit the scene, assign a scale and a coordinate system, add "Reference Points and Lines", and export the Photo Scenes to various file formats such as DWG.

Photo Scene Editor (PSE) can be acquired freely from [http://labs.autodesk.com/utilities/photo\\_scene\\_editor/](http://labs.autodesk.com/utilities/photo_scene_editor/), and runs under Microsoft Windows SP3 or higher.

## 3. PHOTO SCENE CREATION WORKFLOW

The typical steps followed in order to create a photo scene are:

Shooting the right images. This means capturing the right number of pictures from the right angles and positions. (See appendix A)

Creating a photo scene. In this step we choose the desired photos to include in the scene then using the PSE they are processed to the scene and the corresponded point cloud.

1. Editing the photo scene. PSE enables the user to view the 3D cameras and Automatic Point Cloud in a 3D space or through each camera, it also enables us to add reference points, some reference lines and define a coordinate system.
2. Exporting the Photo Scene. After that user is able to export the edited scene in different file formats and to different software.

After creating the scene and exporting it, various software can be used for 3D model creation and editing.

## 4. EARTHWORK APPLICATIONS USING IMAGE BASED 3D MODELING

Image based 3D modeling can be of great use in executing and planning for earthwork projects. The approach was to use Autodesk's technology in two vital applications in earthwork projects. The first is Earthwork Topographic Modeling, and the second is quantities monitoring and calculation.

### 4.1. Earthwork Topographic Modeling

Topography modeling is considered a basic and very important step for earthwork planning. Various tools are used for topography modeling, starting from using conventional survey techniques to the use of software like Google Earth. The major three factors that affect the decision of which tool to use are 1) how accurate the technique is? 2) how long does applying this technique takes?, and 3) how much does it cost to use it?

Considering both time and cost of the image based 3D modeling for earthwork purposes, we can find that this technique has its considerable results although it's not the most accurate one. Applying this tool for earthwork modeling, all the instruments needed were a typical digital camera (Sony DSC-P150, 7 megapixels was used),

the latest version of Photo Scene Editor, and an internet connection.

The process starts as mentioned above by taking pictures. As it was desired to study the accuracy of the technique in proportion to the modeled land area, three pieces of land to model were chosen. The first was a 50 m<sup>2</sup> part of the AUC's (The American University in Cairo) surrounding landscape, the second was "Tabarak" a residential compound which lies in the East of the AUC campus and the third was a bank construction site. The three sites had different soil types and different soil volumes were modeled.

#### 4.2. Quantities monitoring and calculation

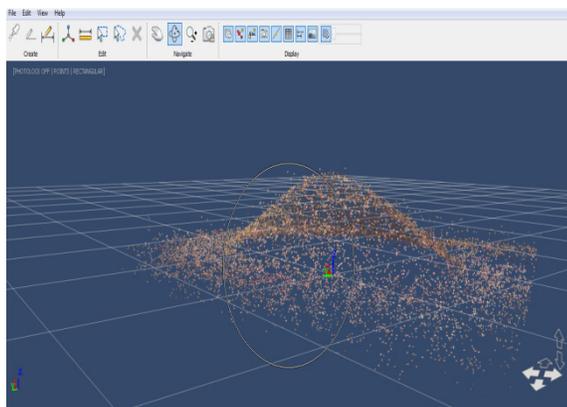
The second application image based 3D modeling technique was utilized in, was measuring and monitoring earthwork quantities on site. Applying such technique can make the process of measuring soil quantities that moved from or to site more robust. It also gives a view for the daily amount of work done.

Mainly this can be done by capturing a series of photos for the amount needed to be measured, the piles stored, or even the holes dug in the work site. After that these photos are modeled through PSE then the output point cloud is exported to Autodesk Civil 3D and a surface is created from it.

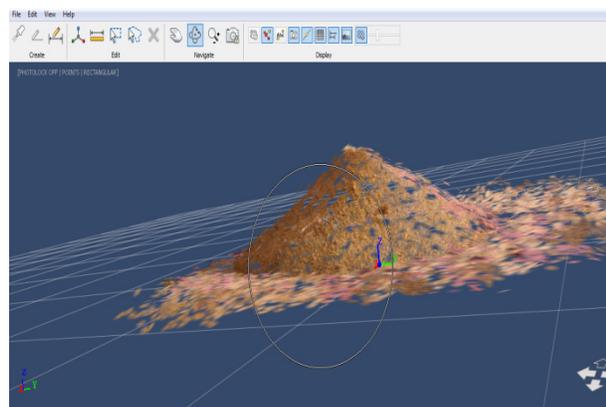
Autodesk Civil 3D offers several tools that can be used in modifying and analyzing surfaces. Using these tools the volume of the modeled surface can be calculated.

The case study for this approach was a test pile taken from a refill sand pile stored in a construction site. The sample was taken using a 930H Caterpillar wheel Loader with a 2.5 m<sup>3</sup> bucket capacity. Two full bucket loads were taken and piled away from the original stored refill soil. Using a determined bucket load helped in determining the exact volume of the sample so it can be compared to the volume that was calculated using the image based 3D modeling technique. According to the used equipment bucket load, the actual volume of the sampled sand was 5m<sup>3</sup>. The Process of modeling started by capturing a series of photos following the guidelines provided in appendix A. Then the 47 captured photos were uploaded to PSE to create the scene, a process took 7 min. After creating the scene (Fig.2), it was exported as two file formats, a DWG file and a LAS file to start modeling the extracted point cloud.

The two exported files are then used in Civil 3D to create a surface from the point cloud resulted from PSE. The steps followed to create the surface are: first the DWG file is opened using Civil 3D. To view the extracted point cloud, a link and index file to the DWG file is needed, which is the LAS file. After creating the point cloud file and attaching it to the opened drawing the user needs to specify more additional data e.g. the insertion point coordinates, the point cloud scale and the rotation angle if any. By this the process of importing the point cloud into Civil 3D is completed and the next step is to model this point cloud to a surface (Fig 3).



(a)



(b)

Fig. 2: (a) The Sample Sand Pile Point Cloud and (b) The Sample Sand Pile Created Scene

After adding Civil 3D properties to the point cloud, the user is able to add these points to a surface; a process known by surface reconstruction. Using Civil 3D allows the user to perform this task in a very simple way, as it offers a tool to add existing point cloud object points to add points to existing surfaces or to create new TIN surfaces. Selecting the effective portion of the point cloud is the last step in the surface reconstruction process, and now a modeled pile into a surface is acquired (Fig. 4).

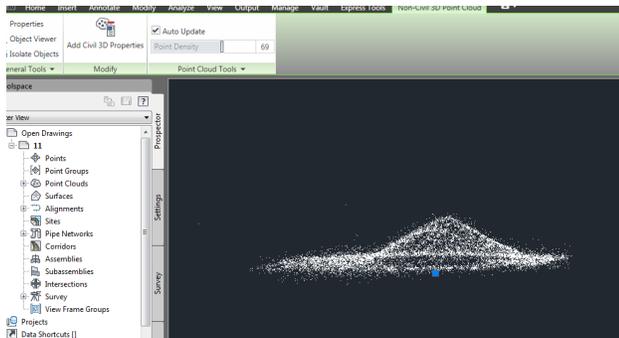


Fig. 3: The Point Cloud in Civil 3D

The new composite surface elevations are calculated based on the difference between the elevations of the two surfaces, as shown in Fig. 5.

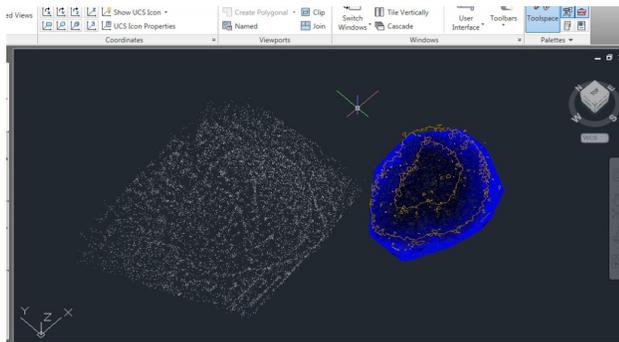


Fig. 4: The Point Cloud and the Reconstructed Surface

The modeled surface is considered as 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 get the most accurate volume. The modeled surface volume was found to be  $4.83 \text{ m}^3$ , with an error equals to  $0.17 \text{ m}^3$  i.e. 3.4%.

## 5. MODEL ACCURACY TESTING

The main three factors that may affect the approach's accuracy are 1) the soil type, 2) number of the photos used to model the surface, and 3) the actual volume of the surface to be modeled. Studying the effect of the soil type on the modeled surface volume was done by modeling four different samples with different soil types. The four samples had the same volume and for each of them the same number of photos was used as PSE input. Table 1 shows the error corresponded to each soil type.

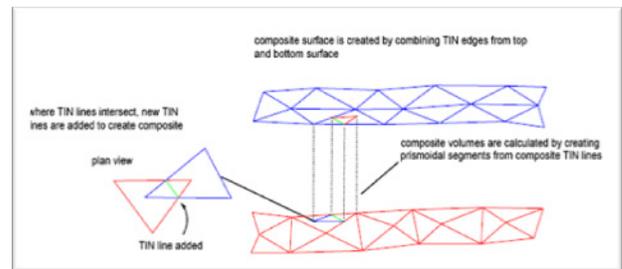


Fig. 5: Composite Surface Elevations Calculation Technique

From these results it can be concluded that the error increases when the soil granularity increases. This may be due to the fact that the more granular the soil sample will be the noisier and spiky the modeled surface becomes.

The second considered factor was the number photos used as PSE input. Table 2 presents the effect of changing the numbers of photos on the model accuracy. As shown in Table 2, increasing the number of captured photos can increase the model accuracy as it will increase the point cloud density. While increasing the point cloud density means increasing the information that point cloud contains and yet increasing the accuracy, excessive number of photos will not have that significant effect on the model accuracy. That was the case when seventy photos were captured.

The last factor tested was the effect of the actual pile volume on the model accuracy. Table 3 shows how the model accuracy changes along with changing the actual pile volume.

The results in Table 3 show that the increase in the pile volume doesn't have a significant effect on the model accuracy.

Soil type	Number of photos	Actual volume (m <sup>3</sup> )	Model volume (m <sup>3</sup> )	% 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

Table 1: The Effect of Changing the Soil Type on the Accuracy of the Modeling Technique

Soil type	Number of photos	Actual volume (m <sup>3</sup> )	Model volume (m <sup>3</sup> )	% 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

Table 2: The effect of Changing the Number of Captured Photos on the Accuracy of the Modeling Technique

Soil type	Number of photos	Actual volume (m <sup>3</sup> )	Model volume (m <sup>3</sup> )	% 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

Table 3: The Effect of Changing the Actual Pile Volume on the Accuracy of the Modeling Technique

This may be due to two reasons; the first is that increasing the pile volume means making its shape more defined and distinguishes it from the surroundings, the second reason is that calculating the error is done by finding the difference between the actual and the model volumes then dividing it by the actual volume. So the increase in the numerator, which represents the difference between the actual and the model volumes, will still be small compared to the denominator (i.e., the actual volume).

## 6. CONCLUSION

The work presented in this paper provides a quantified model of earthwork with the utilization of surface reconstruction techniques to assist general practices in

earthwork, including preliminary planning and measuring cut and fill volumes. Structure-from-motion techniques in earthwork application were used to validate limitations and pros and cons of a 3D surface reconstruction tested in 23 excavation construction sites. By examining the factors that could affect the accuracy of the developed model, it was found that these factors could be summarized into the following: the soil type, number of the photos used to model the surface, and the actual volume of the surface to be modeled. The error resulting from the effect of changing each factor on the accuracy for the model was computed. Based on the values of the errors calculated it can be considered that the model is credible and can be used by contractors willing to utilize this technology in everyday use.

## APPENDIX A

### Shooting guidelines

- Any standard digital camera can be used, with a reasonably high resolution (5 million to 10 million pixels).
- There must be a lot of **overlap** between adjacent Source Photos.
- Each Source Photos must contain some **foreground** and **background** parts in the scene.
- Each area that you want to turn into a 3D point must be seen from **at 3 cameras**.
- Shoot pictures every 10° (roughly) around your scene or object to ensure sufficient overlap between adjacent viewpoints.
- Make sure to see your most important scene content from multiple viewpoints.
- Un-zoom as much as you can to capture the widest possible images, and keep these settings for the entire scene.
- Preferably shoot your close-ups by getting closer rather than by zooming.
- Identify clear areas that you will use to set your scale and your reference coordinate system.
- Measure a reference distance.

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