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AS-BUILT 3D MODELING BASED ON STRUCTURE FROM MOTION FOR DEFORMATION ASSESSMENT OF HISTORICAL BUILDINGS

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ABSTRACT: Assessing the state of historical buildings is non-trivial tasks as limited information is available and only non-invasive assessment can be performed on these buildings. Image-based 3D reconstruction is a recent technique, which can construct an as-built model of a historical building to be used for damage and deformation assessment. The technique is based on Structure from Motion, which can automatically create a 3D model from uncalibrated images. In this paper, VisualSFM, automated image-based 3D modeling software, is applied to construct a 3D model of a historical building. The model is compared with a model obtained from a laser scan (LIDAR). To perform a deformation assessment on the building, a series of a horizontal plane is sliced through the 3D model, and then a centre of each 3D slice is joined to form a line representing an incline angle of the building. This technique is performed against a laboratory dataset to determine its accuracy. It was found that for a small incline angle (less than 4o), the technique contains the inaccuracy of 2.75% with increasing inaccuracy as inclined angles become larger. When applying the technique to a real temple dataset, it was found that the angle of inclination is less than 3o, which is in an acceptable range for the proposed technique. Additionally, it was found that the inclined angles obtained from VisualSFM and LIDAR are almost identical. It was recommended that VisualSFM can be used instead of LIDAR when performing damage assessment in historical buildings.

Keywords: Structure From Motion, As-built Modeling, Damage Assessment, Laser Scan, Historical Buildings

1. INTRODUCTION

Historical buildings are sensitive to damages due to ageing and nearby activities. To assess the damage on historical buildings, the only non-invasive inspection method is possible, and visual inspection is a preferred method. As-built 3D models are now commonly used in archiving historical buildings, as users can use the models to explore and study the buildings more closely off-line. The as-built models can also be used for inspection as demonstrated in this paper.

As shown in Fig. 1, many temples from Ayutthaya have been tilting possibly due to nearby road activities or ground subsidence. The city was founded by King Ramathibodi I in 1350, and in 1969, the Fine Arts department began with renovations of the ruins, which became more serious after it was declared a historical park in 1976. The park was declared a UNESCO World Heritage site in 1991. The scale of conservation and preservation is so large, and many temples have been neglected and deteriorated for many years.

This paper provides further improvement to the study by Bhadakom et al. (2012), who have conducted a study on some Ayutthaya temples to measure tilt angles using traditional photogrammetry techniques. The techniques require control points to be manually identified, and a full 3D model of entire buildings can only be constructed from multiple 3D sub-models. The techniques require 3D registration that is troublesome and induces inaccuracy.

The paper proposed methods to assess damage in historical buildings by estimating how much the buildings are tilted using fully automated software that can create a 3D model from uncalibrated images. The proposed method utilized the 3D model from the software to estimate a tilt angle of a historical building. The methods were tested against laboratory dataset to estimate inaccuracy that can occur from the proposed method of obtaining tilt angles. The 3D model obtained from the software is also compared against the model obtained from a laser scan (LIDAR). It was found that the 3D models from the software and a laser scan provide an identical result when estimating tilt angles and they can be used interchangeably for the purpose of damage assessment and inspection.

Fig. 1 The picture of the temple used in the study.

The subsequent section, Literature Review, summarises previous work in applying 3D modeling in damage assessment. Then, the overview of the method is outlined in Method Outline. In Implementation and Experiment, the proposed method is explained in detail and the results obtained from a laboratory dataset are shown. The result from a real dataset is explained in the section Field Trial, and the paper ends with the discussion of the proposed method and conclusion.

2. LITERATURE REVIEW

Non-invasive inspection is required when assessing damage in vulnerable historic buildings to prevent further damage that can occur from the inspection process themselves [8]. Close range photogrammetry has been used to reconstruct 3D models of historical sites for archiving and for damage assessment purposes [9]. Traditional photogrammetry data collection process requires procedures to identify control points manually, which can become impractical in real sites [4]. Recently, free automatic photogrammetry software packages with computer vision algorithms have been used to create 3D models of historical buildings [3]. The software relies on automatic control point detection algorithms and Structure from Motion, which allow 3D models to be created with ease as images can be taken with arbitrary motions.

Many techniques have been applied in assessing damage in historical buildings using 3D models. The followings are some recent examples. Fregonese et. al. (2013) applied Terrestrial Laser Scanner (TLS) to monitor out-of-plane displacement of an ancient building by registering two sets of laser scan data to several geo-referenced control points. It was concluded that TLS could be used for structural monitoring. El-Tokhey et. al. (2013) transformed control points from a laser scan data to a total station data using a series of transformation to find a discrepancy between two sets of data and displacements. Tapete et. al. (2013) integrated Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR), which can detect deformation of objects between two SAR images, to TSL data. Armesto et. al. (2009) applied TLS to a masonry bridge and the bridge deformation was estimated by an algorithm based on an arch symmetry. Armesto-Gonzalez et. al. (2010) analysed damage in buildings by classification algorithms onto 2D images that were constructed from laser scanner as they can provide other material properties. Bhakapong et. al. (2012) applied photogrammetry technique to compare the cross-sectional profile of temples in order to assess the amount of building inclination.

It can be seen that many recent studies have utilised 3D point cloud to detect damage or changes in historical sites. Most studies use 3D point cloud from a laser scan data, which is believed to be more accurate. However, it is demonstrated in this paper that for some applications, 3D point cloud from images can provide equally good results

3. METHOD OUTLINE

Figure 2 shows the outline of the methods proposed in this paper. The first module is 3D modelling. This module is achieved by free open-source software called VisualSFM, which can create a 3D point cloud model together with camera poses from uncalibrated images. The second module is 3D Registration. The 3D point clouds are registered together so that they are in the same global coordinate frame. The third module is Deformation Assessment, which are achieved by estimating a tilt angle of a 3D model. The detail of each step is explained in Implementation and Experiment.

There are two datasets presented in this paper: (1) a laboratory dataset and (2) a field dataset. The laboratory dataset is used to verify the accuracy of the proposed method, and the field dataset is an actual data obtained from a real site from Ayutthaya. The laboratory dataset is a set of cylinder images taken at 5 angle elevations. The field dataset contains a set of images of the temple and a 3D model of the temple obtained from a laser scan; this is explained in Field Trial.

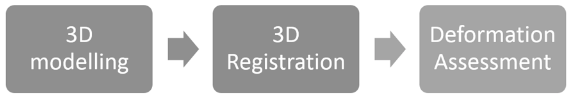


Fig. 2 The outline of the proposed method.

3.1 Modelling

Five sets of images of a concrete cylinder are collected for use in verifying the method in this study. An example image is shown in Figure 3. The cylinder has a diameter of 15 cm and the height of 30 cm, and is placed on a wooden base, in which angles can be adjusted. Sixteen 2x2cm checkerboard pattern are used as control points, which are placed on the cylinder surface. Three 10x10x10 cm concrete cubes are placed on a wooden base; these cubes are used as a reference for registration, explained in the next section.

The five image datasets are taken at different angle elevations, i.e. at 0^o, 2^o, 4^o, 10^o and 14^o degrees, respectively. For each set of images, photos are taken at different viewpoints to cover an entire object using a Canon 550D with a Sigma lens and settings set as Auto. There are no strict rules in how to take images for VisualSFM, although the rule of thumb is to ensure that an overlap between two consecutive images is at least 50%.

A 3D model for each set is created by VisualSFM. This software provides a 3D model and camera poses. The software is based on Structure from Motion (SfM), and interested readers can refer to Snavely et. al. (2006) for more detail of the theory and technology. Figure 4 shows actual 3D models for each angle elevation. The models are 3D dense point clouds, in which their texture is obtained from image pixels. Table 1 provides a summary of the dataset including the number of pictures taken and the number of 3D points created by VisualSFM for each angle of elevation.

Fig. 3 An example picture of a cylinder

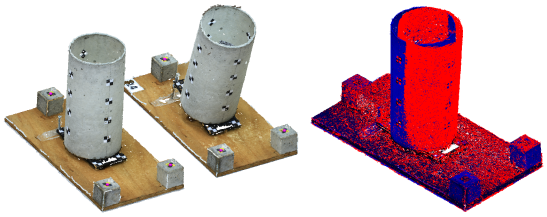
Fig. 4 3D models of the cylinder at 5 angles of inclination.

Table 1 A summary table of the cylinder dataset

Elevation	Images	VisualSFM (points)
0^o	61	342,975
2^o	81	317,737
4^o	79	308,511
10^o	73	350,205
14^o	77	350,972

3.2 Registration

To measure tile angles between different models, the models must be registered so that they are in the same global coordinate frame. The 3D models are registered in the software called CloudCompare [11] using an iterative closest point (ICP) algorithm. To ensure that registration process is accurate, three 10x10x10 cm concrete cubes are used as a reference for registration. As shown in Figure 5, coordinates on the cubes are used for registration, i.e. R_0 is registered with A_0, R_1 with A_1 and R_2 with A_2, and the errors of these points are minimized. Figure 5(b) shows an example of registration between two models using CloudCompare. The model with the elevation angle 0^o is used as a reference model, from which models from other angles are registered and measured the tilt angles. The cylinder is tilted by adjusting a metal base place and real elevations are recorded for comparison explained in the next section.



(a) (b)

Fig. 5 (a) Examples of the model with different tilt angles; (b) the models are registered.

3.3 Deformation Assessment

To find an angle of inclination, a 3D centre line of an object is required. To achieve this for an object that cannot be represented by primitives, such as historical buildings as presented in this study, the following methods are applied. Firstly, the model is sliced horizontally at different heights using slicer in CloudCompare as shown in Figure 6. Figure 6(a) shows an example of a boundary of a slices box in CloudCompare and Figure 6(b) shows horizontal planes that sliced through the cylindrical 3D model. The thickness of each slice is approximately 1 cm so that the sliced point cloud can be assumed as a plane. The planar slices are re-used for all other 3D models to ensure that a 3D model are cut by the same planes. Then, the point cloud from each slice is input into a least square solution for an eclipse. In this study, the shape of a point cloud in a slice is assumed to be an eclipse since the centre can be found easily and the point cloud is not a perfect circle. The algorithm to find the best fit for an eclipse is as follows. An eclipse can be written as

$$\frac{(x-x_0)^2}{a^2}+\frac{(y-y_0)^2}{b^2}=1 \qquad (1)$$

which can be re-arranged to be a form of linear quadratic equations as

$$2b'xy+c'y^2+2d'x+2f'y+g'=-x^2 \qquad (2)$$

For the best fit problem, m data points provides m linear equations, hence the equation (2) for m equations can be written in matrix form as

$$X\beta=y \quad (3)$$

where $X=\begin{bmatrix} 2x_1y_1 & y_1^2 & 2x_1 & 2y_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2x_my_m & y_m^2 & 2x_m & 2y_m & 1 \end{bmatrix}$, $\beta=\begin{bmatrix} b' \\ c' \\ d' \\ f' \\ g' \end{bmatrix}$

and $y=\begin{bmatrix} -x_1^2 \\ \vdots \\ -x_m^2 \end{bmatrix}$.

For the least square problem, the objective function or the residual, $\min \|y-X\beta\|^2$, is minimized. The solution to the equation three can be found as $\beta=X^+y$, where X^+ is a pseudo-inverse of the matrix X. Once the parameters in the vector β are found, they can be converted to major and minor axes, x_0 and y_0 to describe the properties of an eclipse. The center of an eclipse (x_0,y_0) for each slicer is used to estimate a centre line of a cylinder. The angle of elevation is obtained by estimating the slope of a best fit line (constrained at the base) that passes through (x_0,y_0) for all slices.

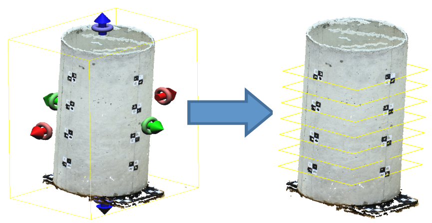


Fig. 6 Examples of horizontal slices used to cut a 3D model.

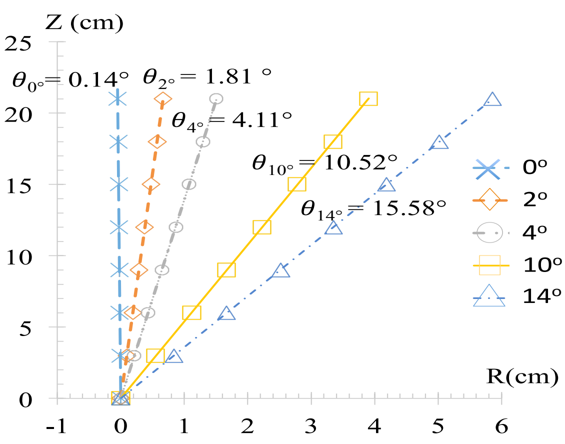


Fig. 7 An example picture of a cylinder

Figure 7 shows the results for all elevations. The slope of each line is converted to angles. The subscripts and the legend indicate the real angles of elevation. The deviation from the real angle is the largest at 11% when the angle is 14°. For an angle of 4°, the difference is smallest, less than 0.11° or approximately 3%. Therefore, when an angle of elevation is around 3°- 4°, the proposed method can provide reasonable results.

4. RESULTS

In this section, similar methods are applied on a dataset obtained from a real site, which is a temple from Ayutthaya historical park.

4.1 Modeling

In this section, two sets of data were collected, an image dataset for VisualSFM and data from a laser scan. The point clouds from these models are used for comparison as explained in a later subsection. The image dataset is used with VisualSFM and the camera used and how the images are obtained identical to the cylinder dataset. There are no strict rules for taking pictures; the rule of thumb is consecutive images must have an overlap of at least 50%.

In the temple dataset, pictures were taken at a distance where an entire building was visible, and then the subsequent image was taken at approximate 3-4 meters from the previous image and the procedure was repeated to obtain images for an entire building. As shown in Fig. 8, the output from VisualSFM shows a sparse point cloud and the locations of where each image was taken. It can also give a dense 3D surface model, in which the point cloud is denser and provides more realistic visualization for a building as depicted in Figure 9(a).

A 3D point cloud from laser scanner was collected for a temple as shown in Fig. 9(b). The 3D laser scanner used in this work is FARO Focus3D. This system requires at least 3 physical control points, where these points must be visible for the laser scan, which can be troublesome to find suitable locations for these control points. Once the locations of control points were setup, the laser scan can then collect the data. The data were collected from 8 locations for each temple in order to obtain point clouds that cover entire buildings. Then the software Faro Scene was applied to register the point clouds from each location to form a single point cloud for the entire temple.

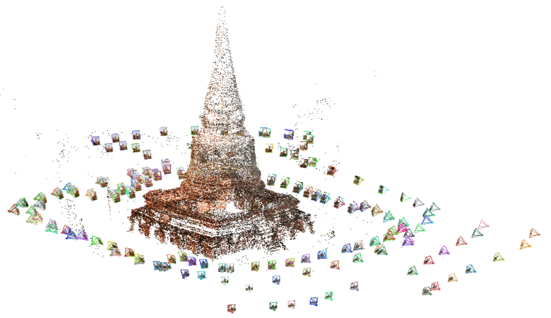


Fig. 8 A 3D model of the temple created from VisualSFM with camera positions.

(a) (b) (c)

Fig. 9 (a) 3D model from VisualSFM (b) 3D model from LIDAR (c) the results of registration between the model from VisualSFM and LIDAR.

4.2 Registration

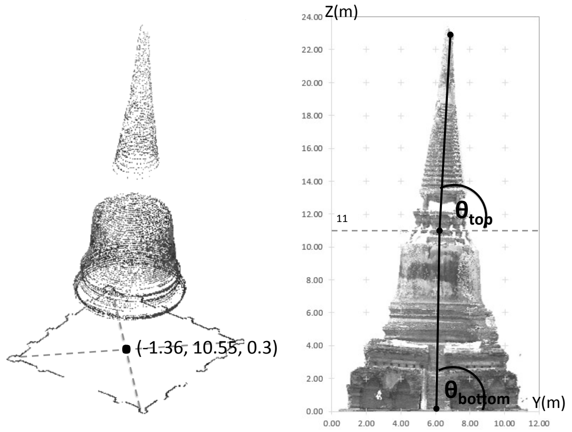
In this section, the comparison is made between models from VisualSFM and LIDAR. The 3D models from VisualSFM and LIDAR are registered in CloudCompare using an iterative closest point (ICP) algorithm, which is applied iteratively until RMS errors between the models are constantly taken as the final RMS error. Initial alignment between two models must be specified as a reference in order to register the models accurately. In this study, the base of the temple was used as the initial alignment. Fig. 9(c) and Tab. 2 shows the results from registration of the two 3D models.

Table 2 A summary table of the registration result between the VisualSFM and LIDAR models.

Data	Small Stupa
RMS	0.0902
LIDAR #points	1,000,000
VisualSFM #points	1,122,143
#points Ratio	0.8911

4.3 Deformation Assessment

As shown from Fig. 10(a), the centre line of the temple starts from the centre of the temple base, which was found by an intersection of the diagonal of the base. In this study, it was assumed that the whole temple does not tilt together as a single rigid object. The temple is split into an upper part with the height between 11 to 22 meters and a lower part with the height from 0 to 11 meters. This is based on the assumption that the top of the temple can move more than the lower part and also the point cloud is more complete at the lower part than the upper part. As shown in Fig. 10(b), the temple will have two tilt angles, $\boldsymbol{\theta_{top}}$ for the upper section and $\boldsymbol{\theta_{bottom}}$ for the lower section. Simlar to the cylinder dataset, the tilt angle is found by a slope of a best fit line to data. Figure 11 shows the results of tilt angles of the temple. The orange line is the LIDAR data and the blue line is the VisualSFM data. Figure 11(a) is the cross section using x-z plane and Fig. 11(b) is the cross-section on the y-z plane. On Fig. 11, it can be seen that the tilt angles on the x-z plane are different on upper and lower part for both datasets, whereas the angles are almost identical to the y-z plane. The tilt angles are almost identical for both datasets, which suggests that the accuracy of the model from VisualSFM is similar to the model from LIDAR. The angle of inclination is between $1^{o} - 3^{o}$, and the laboratory results suggest these angles of inclination are within the range of accuracy tolerance that the proposed method can provide sufficiently accurate results.



(a) (b)

Fig. 10 (a) Show the location of the center of the temple; (b) show angles of inclination of the top and bottom parts of the temple.

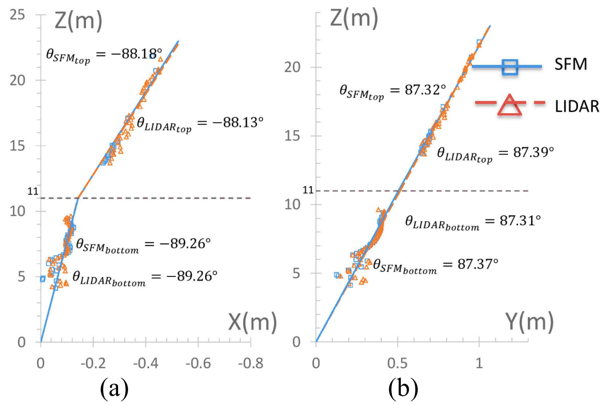


Fig. 11 Shows the results of inclined angles on the (a) x-z plane and (b) y-z plane, respectively.

5. DISCUSSION

It can be seen that the angles of inclination obtained from both LIDAR and VisualSFM are almost identical; this suggests that VisualSFM can be used instead of LIDAR. However, inaccuracy is observed by the proposed method. It can be seen that, from the cylinder dataset, the centres of slices lie well on the best fit line, unlike in the temple dataset. A 3D point cloud model is not water tight. Hence, holes can be observed in many locations. Therefore, some slices may not contain sufficient data points, and the estimation of the centres can be skewed. This problem will be seen in both the models from VisualSFM and LIDAR. Inaccuracy can also arise due to registration between 3D models, this problem is not trivial and further work is required

6. CONCLUSION

To perform damage assessment on historical buildings, the non-invasive inspection method is preferred. This paper presents a method to assess damage on historical buildings by measuring angles of inclination from 3D models. The proposed method provides sufficient accuracy in estimating a tile angle for a small angle as observed in the cylinder dataset. The angles of inclination are identical for both models from VisualSFM and LIDAR, which can be suggested that the model from VisualSFM can be used instead of LIDAR as it provides the same accuracy for this task, and the technology is easier and cheaper to use. The proposed method still poses some inaccuracy in estimating the centre lines due to inaccuracy in a point cloud model. This can be improved by making the point cloud model denser or by converting the point cloud to a watertight surface model. This is planned for further study.

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