3D POINT CLOUD BASED ON STRUCTURE-FROM-MOTION PHOTOGRAMMETRY FOR BRIDGE INCLINATION ASSESSMENT IN MYANMAR

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ABSTRACT: Rapid urban expansion and economic development increases the demand for transport infrastructure in many developing countries. As of 2012, Myanmar has total of 4,728 bridge of which 741 bridge were classified as major bridge. Considering Myanmar vast geography, lack of technological resources and investment caused inadequate and inappropriate monitoring of bridge health. Structure-from-Motion (SfM) photogrammetry provides an economic and user-friendly alternative. Although SfM has been applied in various studies related to infrastructure, its application for bridge structure displacement remains limited. This study aimed to evaluate the application of SfM based reconstructed point cloud in assessing inclination of Twantay bridge's main towers, a suspension bridge located in suburban Yangon, Myanmar. Photosets were obtained around the towers at ground level using a consumer-grade digital camera. These images were processed with SfM workflow on commercial software and the result was then scaled based on known length of object features. A 3D reference point cloud was created using mesh model digitized from blueprint dataset to validate displacement from designed position. Boundary points at the edge of SfM reconstructed cloud were used for calculating distance difference to the corresponding nearest points on the reference cloud in x, y, and z direction. The result showed that the distance difference on the y-axis, a direction facing the river front, gradually increases toward the top part of the tower compared to that of bridge piers. This result suggested that SfM technology can be applied for inclination assessment to provide displacement tendency. However, precise measurement remains a challenge.

1. INTRODUCTION

In Myanmar, rapid urban expansion and economic development increases the demand for construction and upgrade of transport infrastructure to improve connectivity. As of 2012, Myanmar has total of 4,728 bridges of which 741 bridges were considered major bridge spanning 54 m. or longer (Japan Infrastructure Partners 2012). Deterioration and collapse of major bridges potentially leads to local-scale disaster resulting in loss of life and impacting economic activity as logistics are halt. Even though physical measurement methods and various sensors were invented, these knowledge, technology, and investment are sometimes not readily available in such developing countries. Hence, lack of resources can lead to inadequate and inappropriate monitoring of bridge health.

3D information of civil infrastructure can be useful to assess and monitor structure condition. Various methods (e.g. photogrammetry, videogrammetry, laser scanning, etc.) are available and vastly accepted in civil engineering field to collect spatial data for 3D measurement of infrastructure (Zhu & Brilakis 2009). Structure-from-Motion (SfM) photogrammetry, an economic and efficient solution, presents high potential for developing country like Myanmar. SfM algorithm automatically resolves camera orientation and position to extract 3D information by iteratively matching corresponding points in multiple overlapping images (Westoby et al. 2012). SfM technique has gained interest and was applied in many studies related to structure assessment, for example comparison between as-built and as-design for bridge construction monitoring (Bhatla et al. 2012), building damage assessment after disaster (Zhou et al. 2015), and concreate crack detection (Liu et al. 2016). In addition, accuracy of SfM technology has been evaluated (Golparvar-Fard et al. 2011), and even more specifically for structural health monitoring (Soni et al. 2015). Although SfM technology was utilized for displacement of bridge-related structure, its application remains limited to simple plane with clear distinct features, such as gabion walls (Fraštia et al. 2014).

Therefore, the objective of this study is to evaluate feasibility of SfM photogrammetry to assess bridge tower inclination in Myanmar. Utilization of available resources was emphasized, hence data was acquired with consumer-grade camera and minimum pre-setup field work. In addition, commercial SfM software was selected considering ease-of-use in operational settings.

2. DATA & METHODOLOGY

2.1 Study Site

Twantay Bridge, a single-span suspension bridge constructed in 2006, is located in suburban Yangon, Myanmar. The height of its main towers is 44.87 m. and its deck spanning 1,210 m. long. Based on visual inspection during maintenance survey, the main towers were suspected to incline (Figure 1).

Figure 1: Twantay bridge location (study site)

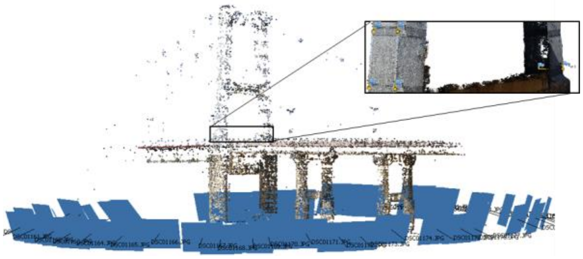

Figure 2: Camera location and points for scaling

2.2 Data Collection

The acquisition of photograph represents challenges from the height of the structure. The study site also posed additional restriction of UAV and drone usage. 55 photos were, hence, taken at the ground level around the towers on 16 February 2016. The survey was performed using a point-and-shoot SONY DSC-RX100M3 with 20.1 megapixel 1-inch sensor. All images were taken with fixed focal length at 8.8 mm, while aperture and sensitivity were automatically adjusted by the camera at f/4-5.6 and ISO125 respectively. In addition, these photos were acquired with minimum of 60% overlap. For this study, images were received without Ground Control Points (GCPs). This image dataset was used to reconstruct 3D point cloud representing as-is condition. For baseline, a blueprint drawing of the bridge was considered as best reference to as-design or the initial condition of the structure.

2.3 Three-Dimensional Reconstruction

The methodology used in this study is shown in Figure 3. Screening for low quality photographs (e.g. blurry images or images with high reflectance occluding the structure) was performed to reduce errors during SfM process. After selection, 52 images were used. In this research, Agisoft Photoscan Professional version 1.2, a commercial software, was used to reconstruct 3D point clouds. Camera calibration is crucial in reconstructing 3D from 2D to ensure model accuracy. As no GCPs were collected for this dataset, two calibration options, pre-calibrated using theoretical checker board and self-calibration option in Photoscan, can be employed. On-the-job self-calibration in Photoscan workflow was tested and demonstrated higher accuracy compared to pre-calibration solution (Harwin et al. 2015). Therefore, Agisoft's built-in self-calibration option was used in this study.

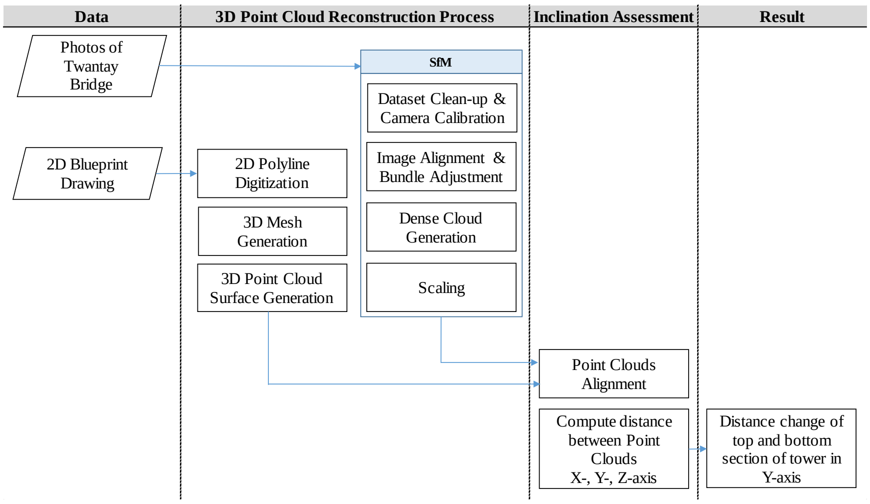

Figure 3: Methodology workflow

The workflow and algorithm of Photoscan were discussed in detail by Turner et al. (2014) and Verhoeven (2011) which was summarized in this section. Initially, an image alignment was applied in which Scale Invariant Feature Transform (SIFT) and Agisoft's algorithm detect correspondent features among images. Bundle adjustment was then iteratively used on matched features to estimate camera's position, orientation, and other parameters. During this stage, the software also automatically corrected radial and tangential distortion using Brown's distortion model. In this study, irrelevant points were then removed using 'Gradual Selection' tool and reconstructed parameters was further optimized. Reprojection error and reconstruction uncertainty were adjusted to improve reconstruction accuracy and reduce noises (Agisoft Photoscan 2015). The workflow continues as the optimized output was used to generate dense point cloud through multi-view stereo reconstruction approach. Through our experiment, high quality and aggressive depth filtering was found to be the optimal settings for dense point cloud reconstruction.

The reconstructed dense point clouds are in arbitrary scale. Known length based on blueprint drawing of the structure were used for scaling. In this study, six points are selected to create three scale bars (Figure 2). The point clouds were exported for inclination analysis. Reference dataset was generated in order to detect change due to inclination effect. The 2D blueprint drawing was digitized and converted into 3D mesh model. Its surface was then exploded into dense point cloud data with density of 1,900 points per m^2 resulting in total of 2 million points.

2.4 Inclination Analysis

To evaluate the inclination of the tower, the distance difference of reference cloud to that of as-is cloud was analyzed. It is assumed that no significant deformation presented at the piers and only the towers are impacted by inclination. If the towers incline as suspected, greater difference in horizontal distance should be observed as height increases toward top part of the towers. In order to compute this offset or distance difference between the as-is and the reference as-design dataset, both point clouds must be aligned in the same coordinate system. Point cloud alignment and distance computation were completed by Cloud Compare (2016), an open-source software.

Alignment between as-is point cloud to the reference point cloud was performed by firstly computing transformation matrix based on point-pair selection of corresponding features among the two point clouds. Six pairs distributed on the piers were chosen. After initial alignment, a finer registration using Iterative Closet Point (ICP) algorithm was applied. Additionally, the scale of each cloud is fixed, so that it was not affected by this transformation.

Distance difference was calculated by cloud-to-cloud (C2C) comparison method which computes distance from each point to the benchmark cloud using nearest neighbor concept (Lague et al. 2013). C2C was chosen because it allows split calculate in each x-y-z axis and also provides signed measurement to show point's location in relation to the benchmark cloud. As-is cloud can contain high noises on the surface especially at area far from the camera and those with limited lighting. Consequently, interpretation of C2C result based on the whole surface can be misleading. Using boundary points at the edge of reconstructed model likely alleviated such effect. Hence, edge extraction was performed on segmented sections prior to C2C comparison by applying 3D Hough Transform (Borrmann et al. 2011). The distance calculated for y-axis, direction suspected for inclination, was analyzed. The piers and towers were examined separately. In addition, boundary points on the tower were grouped based on (i) Tower1 or 2, (ii) river or land side, and (iii) inner or outer edge (Figure 4a).

3. RESULTS

3.1 Model Accuracy

Two sources of error are considered in reconstruction of point clouds: (i) the error corresponding to feature matching in SfM, (ii) the error from scaling process. Since GCPs measurement is not available in this study, Root Mean Square Error (RMSE) of reprojection was computed in pixel which illustrates the quality of camera position and orientation, as well as matching points on the images. RMS reprojection error measures pixel difference between tie point on the photo and the corresponding 3D point projecting back on the same photo. The commonly accepted value of error is recommended to be under 0.6-0.8 pixels (Pasumansky 2015). This model is reconstructed with RMS reprojection error of 0.586 pixel and maximum error of 6.521 pixel.

Table 1: Scaling Error of Reconstruction Point Cloud

Scale Pair	Known Distance (m)	Estimated Distance (m)	Error (m)
Pair1-2	2.200	2.194	-0.006
Pair3-4	2.200	2.202	0.002
Pair5-6	2.200	2.207	0.007
Total Error			0.005

Scaling errors were calculated from the difference between known length from blueprint and that estimated by Photoscan based on manually placed markers. Figure 4a displayed the 3D reconstructed point cloud. Table 1 displayed error of each scaling pair and the total scaling error of 0.005 m.

3.2 Point Cloud Alignment Accuracy

Table 2: RMS Error for Point Cloud Alignment

Alignment	RMSE	Fixed Scale
Point-pair selection	0.173	1.0
ICP	0.536	1.0

The result of point cloud alignment is presented in Figure 4c. Table 2 showed RMS error which indicated level of alignment accuracy. For point-pair selection alignment, RMS measures the remaining distance between each pair after registering the two point clouds. In this study, six pairs were selected and the average RMSE of these pairs is 0.173. ICP was applied for finer alignment. For ICP algorithm, its RMSE is of the distance between each randomly selected points of the as-is cloud and their nearest neighbor in the reference cloud. 50,000 points were used with the resulting RMS error of 0.536.

3.2 Inclination Assessment

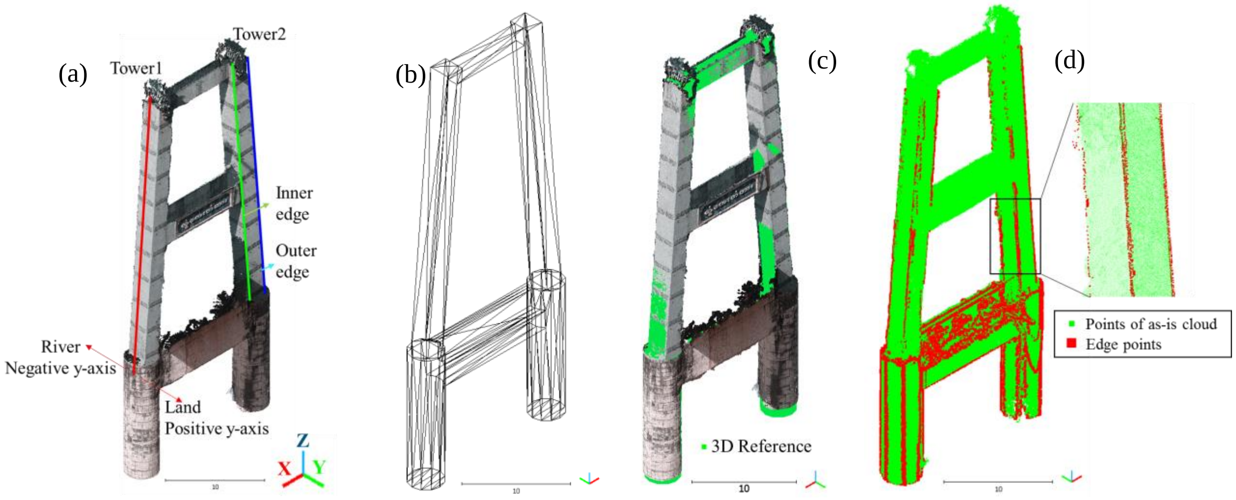

Figure 4: (a) 3D reconstructed point cloud from SfM method
(b) 3D mesh generated from blueprint drawing (c) Point cloud alignment (d) Edge points extracted

To minimize misleading distance due to noises of reconstructed model, only boundary points were extracted as shown in Figure 4d. Since the blueprint drawing does not include details of a center beam between two towers and the design at the tower top (Figure 4b), these portions were removed from edge points extracted from the as-is cloud. Distance difference of the as-is cloud to the reference cloud was calculated separately for x, y, and z-axis. This study focused on the distance computed in y-axis which is the same as the direction suspected for inclination. The computed distance was plotted in Figure 5, which provided a side profile of the towers on yz plane.

From Figure 5, vertical axis represents elevation and horizontal axis represents distance difference of as-is points to baseline in y-axis of the model. The negative and positive sign indicated the direction of points in comparison to the baseline. The positive value implies that distance of the as-is points are located further away from the baseline toward land side, while the negative sign means that distance of the as-is points are toward the river side in comparison with the baseline. For piers which have cylinder shape, only the edge on each side in xz plane were plotted. Looking at the pier edge points, the result showed that as-is points on each side were located further outward from the baseline. This suggested that piers of reconstructed cloud are overall bigger compared to reference cloud. Interestingly, the distance was observed to be gradually shifting more and more toward the positive axis (land side) as height increased. The tower points, on the other hand, can be seen that their overall distance was leaning toward the river (negative) as elevation increased toward the top of the tower. Hence, the piers seem slightly shifted toward the land away from the baseline, while the towers were clearly inclined toward the river compared to the baseline.

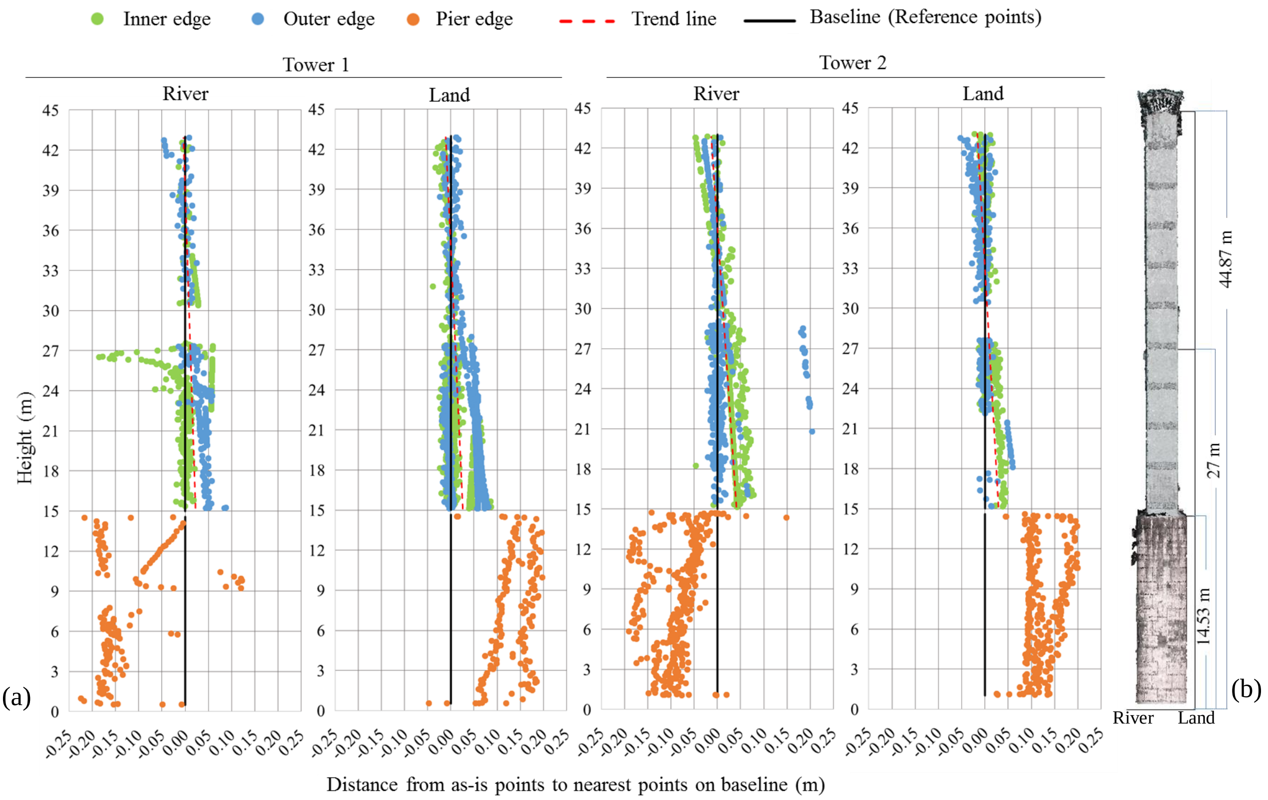

Figure 5: (a) Distance between as-is edge points to nearest reference points (b) Height reference

Table 3 summarized the horizontal change between an average distance of points at the bottom one meter of the towers and that of the top one meter. The overall horizontal distance change as the height of the tower increased was around 3-6 cm. This has not taken into consideration uncertainty from SfM reconstruction and scaling process.

Table 3: Horizontal distance change between top-bottom of tower: Tower1 (left) Tower2 (right)

	Line	Horizontal Distance Change (m)
Y-negative (River)	Inner	0.002
	Outer	0.079
	Average	0.041
Y-positive (Land)	Inner	0.043
	Outer	0.043
	Average	0.043

	Line	Horizontal Distance Change (m)
Y-negative (River)	Inner	0.073
	Outer	0.045
	Average	0.059
Y-positive (Land)	Inner	0.040
	Outer	0.028
	Average	0.034

4. DISCUSSIONS

The overall result from C2C comparison suggested a tendency that the towers are inclining toward negative y-direction or toward the river side. The reconstructed model can capture detail of the structure (e.g. the bump on Tower1 around 27m from the ground). However, in order to provide precise measurement, uncertainty in model reconstruction and cloud alignment must be minimized and incorporated. Result of alignment yielded significantly high RMSE of 0.53 m, although visual validation of the result (Figure 4c) presented much less errors. The high RMSE can be caused by the obvious discrepancy of features between the built structure and the blueprint design (e.g. center beam, etc.). In addition, Turner et al. (2015) indicated inconsistent translation parameter in ICP due to its converging to local minimum leading to high RMSE. Therefore, direct use of this uncertainty will mislead the result. Similarly, although the error of SfM model was within that recommended by the vendor, its result is available in pixel unit. Hence, incorporation into inclination distance cannot be done directly. Additionally, noises in the model also possibly caused variation of measured distance among each edge shown in Table 3. Although camera quality can directly impact level of noise, the result also illustrated the effect of lighting condition. As the photos were taken in the afternoon, one side of the structure received more light (Tower1) which resulted in more available points, less noise and sharper detail.

Nevertheless, even with limited resources and constraint of precise measurement, this study suggested that SfM technology can be applied to provide systematic assessment for tower inclination tendency. Besides its low-cost and ease-of-use, SfM method also does not require long time during field survey. Additionally, the acquired data can be digitally stored for future comparison. Hence, this quick assessment and its computed trend may be an indicator for engineers to prioritize the inspection work.

5. SUMMARY & FUTURE WORK

Limited resources in developing country such as Myanmar can lead to inadequate monitoring of rapidly constructed logistics infrastructure. This research attempted to evaluate the application of SfM method with commercial off-the-shelf camera as an economic solution for bridge structure inclination assessment. Due to restriction of UAV and drone usage, the photos were acquired at ground level. After screening for image quality, photos were used in SfM software to reconstructed 3D point cloud representing as-is condition. The scaled as-is cloud was aligned to 3D reference cloud generated from 2D blueprint drawing. Boundary points of as-is cloud were extracted and used to calculate distance to nearest points on reference cloud which was considered as baseline. The inclination can be assessed from this distance change as the height of the tower increases. The result suggested that the towers incline toward the river side with horizontal distance change between bottom and top of tower estimated to 3-6 cm (± 0.5 cm). Due to a constraint on ground truth validation and discrepancy in some parts of drawing design used for reference to that of actual built structure, uncertainty of model reconstruction and point cloud alignment cannot be directly incorporated into the estimated result. In all, this study demonstrated that SfM technique can be applied to indicate general trend of bridge structure inclination which may be used as indicator for prioritization of inspection work. However, precise measurement of inclination level is still limited.

For future work, comparison of different camera grade can be performed. Due to the quality of the current camera, especially the size of the sensor, noises were presented in the model. Hence, comparison between point-and-shoot camera and entry-level DSLR to check if significant improvement can be achieved. In addition, further validation with ground truth data acquired by Terrestrial Laser Scanner can be performed. Lastly, to assist engineers identifying appropriate countermeasure, it is crucial to determine cause of structure deterioration. Hence, integration of various remotely sensed data can be executed to validate possible land subsidence and effect of flooding on site of the structure.

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