DATA PROCESSING WORKFLOWS FROM LOW-COST DIGITAL SURVEY TO VARIOUS APPLICATIONS: THREE CASE STUDIES OF CHINESE HISTORIC ARCHITECTURE

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ABSTRACT:

The paper focuses on the versatility of data processing workflows ranging from BIM-based survey to structural analysis and reverse modeling. In China nowadays, a large number of historic architecture are in need of restoration, reinforcement and renovation. But the architects are not prepared for the conversion from the booming AEC industry to architectural preservation. As surveyors working with architects in such projects, we have to develop efficient low-cost digital survey workflow robust to various types of architecture, and to process the captured data for architects. Although laser scanning yields high accuracy in architectural heritage documentation and the workflow is quite straightforward, the cost and portability hinder it from being used in projects where budget and efficiency are of prime concern. We integrate Structure from Motion techniques with UAV and total station in data acquisition. The captured data is processed for various purposes illustrated with three case studies: the first one is as-built BIM for a historic building based on registered point clouds according to Ground Control Points; The second one concerns structural analysis for a damaged bridge using Finite Element Analysis software; The last one relates to parametric automated feature extraction from captured point clouds for reverse modeling and fabrication.

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1. INTRODUCTION

Digital techniques have been applied to architectural heritage worldwide, while China's numerous historic architecture are barely involved in this tendency yet. Except a few monuments considered as symbols beyond architecture (eg. the Forbidden City), most historic architecture are not even documented. The government leaned much effort to preserve the ancient monuments, but it is far from enough given the vast amount of architectural heritage ranging in epoch and type.

In recent years there is a growing need of preservation for historic architecture through nongovernmental approach - architectural service market. Compared to the old government-led approach, the architectural service market is much more flexible and efficient. But neither the managers of historic architecture nor the architects are ready for the conversion from the booming AEC industry to architectural preservation. The managers are not willing to spend more money and time on survey, since they are not aware of the necessity of data acquisition to intervention. The architects were trained with limited knowledge and techniques of data acquisition and data processing in school. The manual survey widely used in such projects dose not give rise to detailed documentation and potential data processing due to inaccuracy and file format.

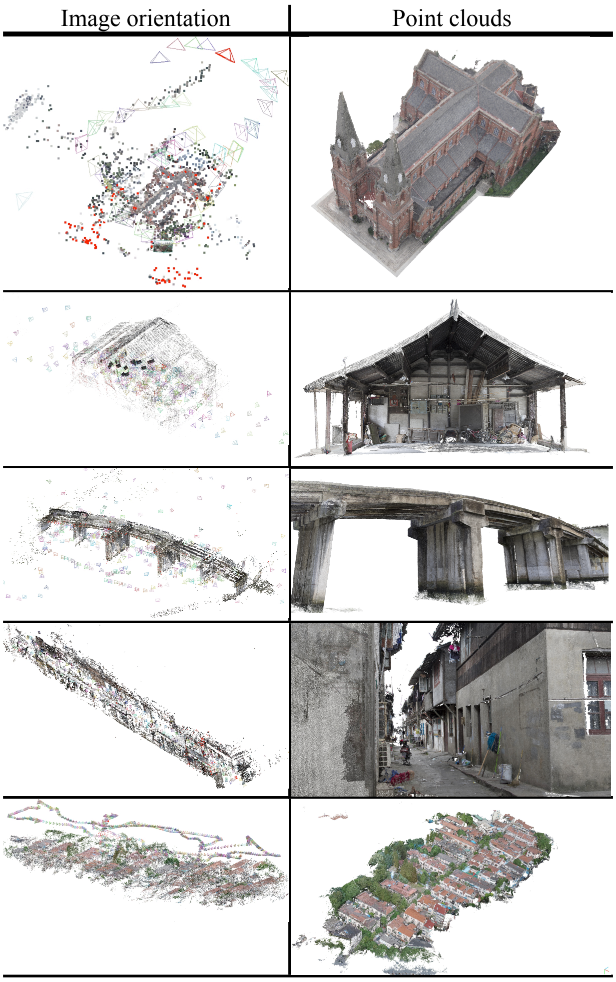

Figure 1. Low-cost digital survey techniques versatile to various types of architecture

As surveyors working with architects in such projects, a frequently asked question by architects is 'how can we use this data?' Therefore, on one hand we have to develop efficient low-cost digital survey workflow robust to various types of architecture (figure 1), on the other hand we are supposed process the captured data for architects who barely know how to deal with point clouds or mesh.

The paper focuses on the data processing workflows towards three different applications. Although unsolved problems exist, it show the versatility of application provided by low-cost data acquisition techniques. The practices of data processing reported in the paper were completed during September, 2014 to January, 2015. It reveals the growing demand for digital documentation instead of conventional manual survey today in China, and the necessity of versatility in data processing.

2. DATA ACQUISITION TECHNIQUES

Although the metric accuracy still has to be further studied, SfM techniques are promising in automated image orientation and 3D reconstruction in large complex scenes (Remondino, 2012). Combining the automation of SfM with photogrammetric methods for improved accuracy is under way. Efforts have been made from different procedures of the process including feature descriptors (Apollonio, 2014) and image enhancement (Ballabeni, 2015). A successful application of SfM techniques to large-scale architectural heritage is presented in (Gaiani, 2015).

Our data acquisition techniques integrate Structure from Motion techniques with total station and UAV. Total station collects Ground Control Points (GCP) which are used for improving and evaluating metric accuracy as well as model registration. UAV is integrated with SLR camera in image acquisition.

2.1 Improved camera network and image processing

We combine the automated SfM workflow with improved camera network and image processing in data acquisition for better accuracy and efficiency.

The SfM workflow could be carried out either in commercial software or open source software. The commercial software (eg. Agisoft PhotoScan) provides a complete user interface and allows integration of camera calibration and GCP, but the algorithms are unknown due to commercial reasons and consequently allows limited improvement in the workflow. Open source software (Wu, 2011; Furukawa, 2010; Rothermel, 2012; Kazhdan, 2006) enables users to improve the results in each procedure ranging from feature descriptors to dense reconstruction and mesh surface generation.

The camera network plays a fundamental role in the accuracy and completeness of reconstructed model. The convergent camera network and large baseline to depth ratio are favorable to the accuracy, but it also has to consider occlusion, completeness and efficiency in complex scenes. Objects with abundant texture (eg. brick) and few repetitive patterns could be used for markerless camera calibration (Barazzetti, 2010), and to initialize the 3D reconstruction. Most SfM systems are incremental in image orientation (Agarwal, 2009). Initializing from a well-matched image pair, 3D model is reconstructed and grows by repeatedly triangulating new cameras until no new cameras yield the minimum requirement of inlier matches. The incremental procedure employs bundle adjustment and outliers filter to reduce projection errors, but the misalignment still accumulates as the model grows. Therefore, initializing from a solid camera network would improve the accuracy. Ensure the necessary coverage of image acquisition in complex scenes is important. Semantically dividing the architecture and designing camera network separately is a good practice. For instance, a portico could be semantically segmented to facade, vault, column and floor. Designing the camera network for these components, and finally integrate them to a single camera network will increase the probability of sufficient coverage.

The raw images without processing contain a series problems ranging from chromatic aberration to low-texture surface. The chromatic aberration draws a negative influence on feature correspondence and texture mapping. It could be solved by color calibration: A ColorChecker is embedded in captured image and used for further correction of white balance. Then the color profile of the image is extracted and evaluated. Finally the color profile is assigned to the other images with similar illumination conditions and camera orientation angle.

2.2 Total station

The direct output model of SfM is neither in scale nor correctly located when opened in 3D software. At least one known distance is needed to scale the model, and at least three known points could correctly locate the model. Such points could be measured by total station. In addition, abundant GCP could be used to improve and evaluate the metric accuracy of the model especially when uncalibrated camera is used. More importantly, local coordinates established by GCP enables registration of separately reconstructed model. This is very practical in complex architecture where different parts (eg. south facade and north facade) are isolated by trees.

2.3 UAV

The consumer UAV is now an affordable device in data acquisition. It allows better efficiency than terrestrial image capture for architectural scenes such as small village, residential areas and pagoda. The current problem is that the consumer UAV is not equipped with SLR camera but camera with fisheye lens (eg. Gopro) which causes serious radial distortion (Wu, 2014). Studies have been developed to improve the metric accuracy by camera calibration (Balletti, 2014). (Bolognesi, 2015) tested the metric accuracy of DJI Phantom 2 plus Gopro Hero 3+ Black edition. The results show the accuracy is satisfactory when integrated with GCP, and the low-cost UAV could definitely fulfill the data acquisition for architectural heritage. We use the improved version of DJI Phantom 2: DJI Phantom 2 Vision+ and its own camera. GCP obtained by total station is integrated to ensure the metric accuracy.

3. DATA PROCESSING WORKFLOWS

The emerging digital techniques are creating more opportunities to digital representation of architectural heritage, as in the interactive relationships among data acquisition techniques, BIM and generative tool (figure 2).

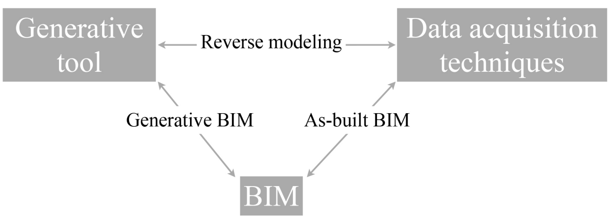

Figure 2. Interactive relationships among emerging digital techniques

Generative BIM integrates the power of rapidly produced multitudes of options of generative tool with semantic structure of BIM, leading to various workflows ranging from structural analysis to form finding, building energy analysis and environmental impact and physic simulation (Mirtschin, 2011). The capability of generative tool in modeling organic form is also used to improve the geometric description in BIM.

BIM is a semantically structured platform allowing data enrichment from multiple sources (Eastman, 2011). In contrast to as-planned BIM, as-built BIM relies much on data acquisition (Volk, 2014), but bridging the gap between raw survey data and semantic model is not an easy task. As-built BIM is still in infancy (Hichri, 2013).

The real-time variance generation of generative tool could also be used to captured data in reverse modeling, such as feature extraction and structuring unsegmented data. In such case the point clouds should be converted to NURBS instead of mesh for more flexible modification.

3.1 BIM-based survey: Student club at Wuhan University

Most current researches focus on transforming laser scanned point clouds to BIM (Garagnani, 2013; Dore, 2014; Oreni, 2014), while photogrammetric approach could also be used in data acquisition if the accuracy and completeness are guaranteed. Taking into consideration of its flexibility, low-cost and integration with UAV, the photogrammetric approach is an promising data acquisition tool for as-built BIM.

Student club at Wuhan University was one of the buildings that constitute the campus which has been categorized as Major Historical and Cultural Site Protected at the National Level. The building was first built in 1930s and enlarged several times since then. Designed by American architect F.H.Kales, the building, along with the others in the campus (office, laboratories and stadium) are representation of traditional Chinese architecture with modern material (concrete, steel).

The student club also has a historical meaning. As one of the most prestigious university in China when the Second World War outbroke, the club witnessed a remarkable speech by Zhou Enlai as well as other important personage such as Chiang Kai-shek.

The building is now poorly maintained in contrast to the glorious past. Now the ground floor is served as dinning hall and kitchen. The first floor is used for rehearsal and occasional performance. The building has not been surveyed after its completion. The latest archives we found were dated back to the 1930s when it was just built.

BIM is served as the central data platform for integrating various data for future intervention. Laser scanning is an ideal solution to data capture, but it is not available due to the limited budget of project. The photogrammetric approach combined with total station and UAV is used.

Merely reconstructing the exterior of the building would make the data acquisition easy, but it is not sufficient for modeling the whole building in BIM. We tried also to reconstruct the major interior space along with the exterior for a single complete model that could be traced for modeling in BIM. Linking the transition between exterior and interior as well as between ground floor and first floor by images is not practical due to occlusions, inefficiency and potential inaccuracy caused by unfavorable camera network. The solution is to align the separately reconstructed model to the same local coordinates according to GCP (figure 3). The local coordinates was established by total station with 9 stations covering and linking all the separate areas. Markers were well-distributed to ensure that each separate model has at least 7 GCP. More than 800 images were captured by SLR camera and UAV. The GCP is also used to evaluate the accuracy. It shows that the error is around 2cm-4cm. The error is mainly caused during setting up stations and the radial distortion of fisheye lens. But the accuracy is sufficient for modeling in BIM given the building's length over 150m.

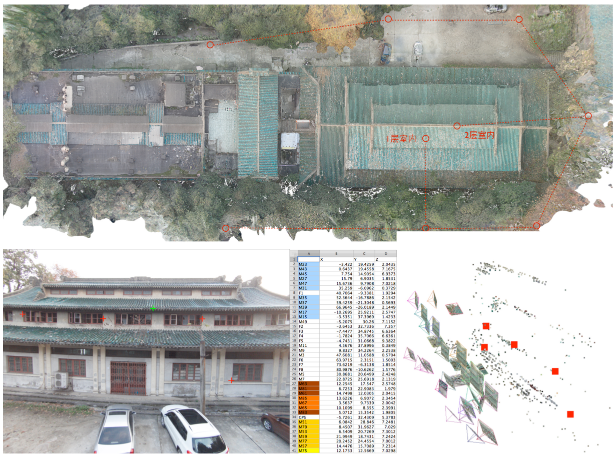

Figure 3. Setting up stations and integrating GCP with point clouds

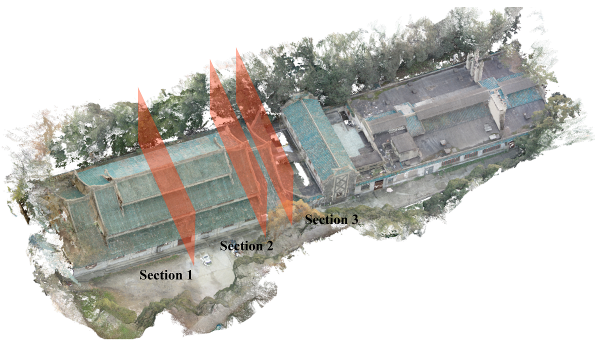

Figure 4. The final registered model allowing random slices for section

The final registered point clouds provide adequate information for modeling in BIM (figure 4). It includes dimensions of components that cannot be measured manually (eg. thickness of ceiling) and relationship between components in different space. Section could be extracted from any positions to ease the modeling in BIM (figure 5 - figure 7). The central platform of BIM avoids the possible data inconsistency in conventional CAD. Associative modeling among internal documents improves the efficiency of as-built documentation by real time model adaption and automatic clash detection.

The automated documentation files in BIM includes drawing, 3D model, rendering (figure 8), and temporal evolution. Besides, the overlap of as-built model (point clouds) and ideal model (BIM) gives access to analysis of deviation. For example, the ceiling and beam system could be modeled by tracking the point clouds. The accuracy level of the as-built BIM could be analyzed using Autodesk Point layout in Revit (figure 9).

The on-site survey lasted for 5 days and the data processing lasted for one week. The conventional manual survey was still carried out in this project, since the reliability of photogrammetric data acquisition in this project was unsure at the beginning. Besides, it is an effective way to measure the dimension of small minor space (eg. kitchen). The projects show that the photogrammetric method could be integrated with manual survey in complex architecture as a substitution of laser scanning in low-budget project.

Figure 5. Section 1

Figure 6. Section 2

Figure 7. Section 3

Figure 8. Rendering of the model

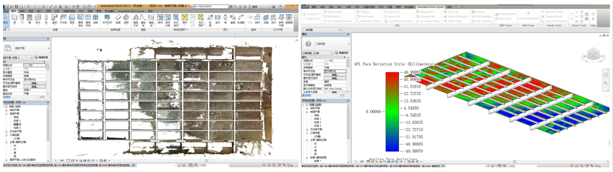

Figure 9. Modeling the beam system in BIM based on point clouds and analyzing their deviation

3.2 Structural analysis: Linzhi Bridge

The data acquisition techniques give access to more accurate structural analysis than the conventional simplified model which is error prone due to the lost of details. One of the crucial step is the conversion from point clouds to Finite Element Analysis (FEA), the predominant tool in engineering analysis. (Barazzetti, 2015) studied the conversion between point clouds to geometrically prepared model for FEA via BIM. But in projects where the semantic distinction is less obvious, we used a more efficient approach that could immediately simulate the structural deformation and allow further development by comparative studies on variables of simulation.

Linzhi Bridge is a single-arch stone bridge built during the era of Qianlong Emperor (1662 AD -1722 AD) and rebuilt during Jiajing (1796AD - 1820AD). Spanning across a 20 meter-wide river in suburbs of Shanghai, the bridge is threatened by increasingly busy shipping. In the last decade, it was collided by cargo ships several times, one of which caused cracks on the deck and deformation on the arch. The bridge was consolidated several times without any detailed documentation. After a new collision in September of 2014, We were consigned to provide solutions for restoration. I

The reason of continual collision was obvious. The span of arch is not ample enough to the size of fully loaded ships, and it becomes even narrower when the ship returns with sharply declined waterline after uploading. Consequently it was always the same part of bridge was under threatening of ship collision. (figure 10).

Figure 10. A ship passing the bridge with extreme carefulness and possibility of collision

We tried to carry out the structural analysis based on as-built model. Both SLR camera and UAV were used for prepare input images for 3D reconstruction in Agisoft Photoscan. The 3D mesh model was registered to local coordinates established by total station. The mesh model was processed in Rhino and simulated using its plug-in, Scan and Solve, FEA software. A series variables were supposed to be specified for structural analysis (table 1).

Variables	Values
Material of bridge	Marble
Volume of bridge	As-built model
Surface load	Weight of ship
	Speed of ship
	Duration of collision
Restraints	Joints to riverbank

Table 1. Variables and values for structural analysis

This structural analysis could not replace rigid structural calculation due to the employed mathematical model: it simulates linear static behavior of 3D solids based on mathematical theory of linear elasticity which idealizes physical reality (Scan and Solve, 2013). Besides, the values such as weight of ship, speed of ship and duration of collision were all estimated. But it provides an immediate visual impact to the stakeholders, and allows further development based on comparative study of the estimated variables. From a technical point of view, the project show an interesting workflow from low-cost data acquisition techniques to structural analysis (figure 11).

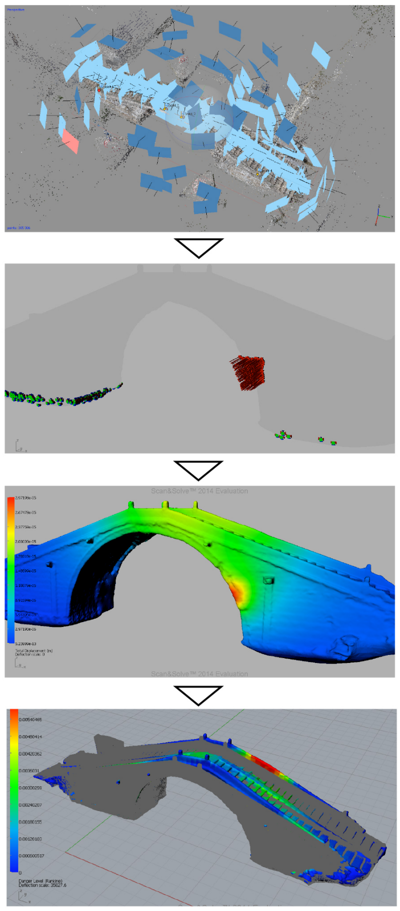

Figure 11. Workflow from image orientation to structural analysis

3.3 Reverse modeling: Shikumen

The direct output of photogrammetric approach are not an ideal source for architects, who suppose the point clouds and mesh as the end of data acquisition, but not source allowing further modification. Architects without training are not able to process such raw survey data. The combination of captured data and generative tool is a promising field. The real-time parametric variance generation of generative tools could be used to extract the features from the captured data. (Coutinho, 2013) used generative tools for automated parametric profile extraction from laser scanned point clouds. Using the same software (Grasshopper, plug-in for Rhino), the case study below is an experiment to link the bridge between captured data and reverse-modeling.

Shikumen, also named Stone Warehouse Gate, is one of Shanghai's most unique architectural typology appeared in 1860s. It is a combination between western decorative styles and local handicraft. Built by bricks and plasters, Shikumen has a wide range of patterns and constitutes the fundamental features of old town at Shanghai.

There is a project of making replica of various patterns of Shikumen with sliced metal plates and locating them in streets, shopping mall and schools. The ideas is to let people appreciate the architectural heritage in their modern daily life.

The data acquisition is quite straightforward using the photogrammetric workflow. As entrance of lane, Shikumen is not occluded by trees and has ideal size (ca. 3m*4.5m) for close-range image acquisition. The challenge is how to extract the cross sections from the point clouds or mesh.

Manually making intersections for one Shikumen model is not a challenging task, but the job becomes intensive and tedious given the large amount of Shikumen. In addition, the time-consuming manual extraction of profile is irreversible which is unfavorable to the frequent modification of interval and thickness of metal plates. Another challenge is how to transform the extracted slice into closed loops. The extracted profiles from the mesh surface are curves, but the metal plates for fabrication should be modeled from closed loops. Manually closing the loop dramatically increases the labor intensity.

We develop a workflow that transforms point clouds to NURBS surface in Rhino and parametrically extracts its profile with a code written in Grasshopper (figure 12). The reversible workflow allows potential modification and the output is compatible with CAD and SketchUp:

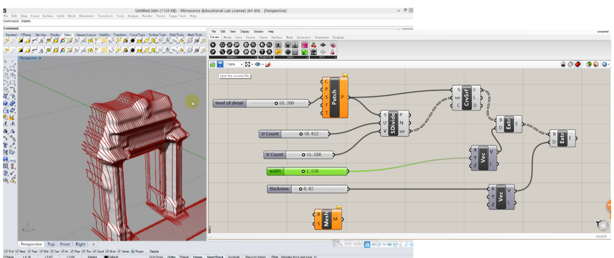

Figure 12. Extracting the profiles of captured data by generative tool

- Generating NURBS

Point clouds are made into NURBS by 'patch' command, during which level of details could be manipulated by parameters 'Surface U spans' and 'Surface V spans'.

- Profile extraction

Curves are extracted from the NURBS surface. The interval of metal plates are defined as parameters allowing potential modification.

- Generating surface from profile

The extracted curves are extruded to surface and volume. Once the model is baked, it could be exported to Autocad (via .dxf) and SketchUp (via .dae) for further modeling.

The code could be easily used by architects without any skill in handling point clouds or mesh. It greatly improves the efficiency of the project, especially when the parameters of interval and thickness are unsure (figure 13).

Figure 13. Workflow from point clouds to parametric slices via NURBS instead of mesh

4. DISCUSSION: UNSOLVED ISSUE

Another widely demanded data processing application is deviation analysis for historic architecture. This is interesting not only for the automated calculation, but also because it provides an intuitive model that could be well understood by amateurs compared to conventional method presented by a series of points. But one of the critical problem is how to define the ideal model to which the captured data is compared.

In order to analyze the degree of an potential inclined wall, for example, a reference plane which is vertical to the XY plane could be used to campare with the correctly located point clouds by GCP. But due to the uncertainty in XZ plane, only the deviation in Z axis is valuable (figure 14). The deviation of two sides of the wall may be actually caused by the arbitrary location of the reference plane.

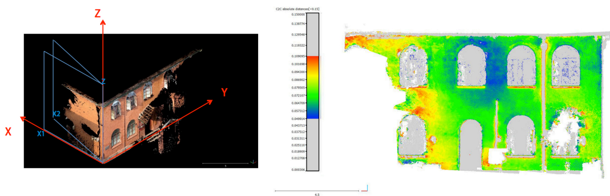

Figure 14. The deviation analysis of an inclined wall is partially meaningful due to the uncertainly of reference plane in XZ plane

Finding the ideal arch of an ancient bridge for analyzing the uneven settlement of the deck is more challenging. Failing to describe the geometry, we have to compare the deck with a horizontal plane (figure 15). Whether the ideal geometry of arch exists in a bridge, and how it is defined in terms of mechanics and historic deformation are to be studied in the future.

Figure 15. Analyzing the uneven settlement of the deck of a bridge by comparison with horizontal plane

Modeling the pagoda by photogrammetric method along with UAV and total station is very efficient, but the problem is how to calculate the tilt of pagoda. We tried to create a cylinder by extruding the circle sharing the same center with the octagonal ground floor plan (figure 16). The point clouds on each floor are then compared to the cylinder to reveal their distance which relates to the tilt of pagoda. But the process if error prone due to a lot of factors: the imperfect geometry of ground floor plan, finding its center and errors in image orientation, etc.

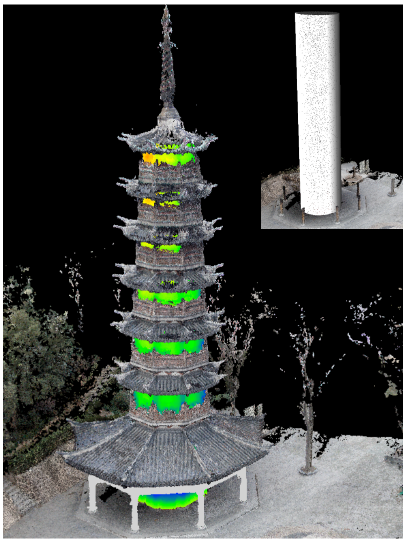

Figure 16. Analyzing the tilt of a pagoda by comparison with cylinder extruded from the circle sharing the same center with the octogonal ground floor plane

Although analyzing the deviation of captured data by comparison with ideal geometry is difficult, it is straightforward to compare the model captured in different time by registration to external reference. In this way the tendency of structural deformation could be monitored.

5. CONCLUSIONS

The low-cost data acquisition techniques enable the digital representation of historic architecture with better accuracy, efficiency and completeness. Doors are opened towards various workflows ranging from as-built BIM to structural analysis, reverse modeling and analysis of deviation. The paper shows that bridging the gap between raw survey data and various applications is promising to architectural heritage documentation and preservation.

We present in this paper the versatility of data processing established on low-cost digital survey with the projects we participated during a short period with three case studies. The first case study show that the integration of SfM techniques and total station could be a substitution of laser scanning in low-budget projects, and gives rise to as-built modeling in BIM. The second case study reveals a workflow from low-cost survey techniques to structural analysis for a damaged ancient bridge. Although the structural analysis uses an idealized mathematical model based on estimated variables, the structural analysis of FEA based on as-built model is a promising field in architectural heritage preservation. The last case study revolves reverse modeling from captured data. Mesh model limited in further modification makes the reverse modeling process a time-consuming and labour-intensive process. Generative tool enables parametric feature extraction from captured data via NURBS. The results could be exported to software familiar to architects for further processing. The reversible process is automated and efficient to potential modification in detailed extraction parameters (eg. level of detail, interval and thickness).

The future developments might be addressed in more robust data acquisition techniques with the development of UAV and sensors. BIM-based survey, structural analysis based on as-built model, reverse modeling by generative tool and deviation analysis will benefit from the interaction among the emerging digital techniques with more accuracy and automation.

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