APPLICATIONS OF INTEGRATED DIGITAL TECHNOLOGIES FOR SURVEYING TIBETAN ARCHITECTURAL HERITAGE:

Three Years of Experiences

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Abstract. Absence of reliable and accurate surveying of Tibetan architectural heritage has long been a major constraint for architects, architectural historians and archeologists working in that region. Due to distinctive geographical environment and architectural typology, unique surveying technologies are required in Tibet. In the last three years, integrated digital surveying technologies are applied to architectural heritage in Gyantse, a Tibetan city. The aim of the surveying is to document and analyze local architectural heritage for potential technical intervention such as consolidation, restoration and renovation. Key technical issues ranging from reliability of consumer-level UAV to BIM-based platform are presented in the article. The conclusions are that digital technologies greatly improve architectural heritage surveying in Tibet in terms of accuracy, efficiency and versatility. Future works will be addressed in more robust algorithms for points cloud semantic segmentation, change detection of large-scale architectural heritage based on remotely sensed imagery over time, and data exchange and coordination between BIM and GIS, etc.

Keywords. Architectural heritage; Digital survey; Tibet; UAV; BIM.
1. Background

The scientific study of Chinese architectural heritage dated from the pioneering work of Institute for Research in Chinese Architecture (IRCA) in the 1930s. Liang Sicheng and his colleagues discovered, surveyed and studied some of the earliest wooden architecture in the North China Plain. IRCA’s research exerts tremendous influence on succedent researchers. Today, architectural historians still have strong passion on the same region and the same architectural typology. Advanced surveying technologies are employed to capture millimeter-level 3D data which arise new interpretations on Liang Sicheng’s work. This is an evident case how architectural history research and heritage conservation benefit from the improved completeness and accuracy of surveying.

In sharp contrast to the wooden remains in North China Plain, absence of reliable metric data has long been the fact in Tibet (Wang 2004). Tibet takes up 1/8 of the country’s 9.6 million square kilometers territory and it is the world’s highest region with averaging altitude over 4000 metres. The shape grammar of Tibetan architecture is distinctive from the wooden structure in North China Plain. Multicultural influence from India and Nepal are reflected in Tibetan architecture. The architectural typology ranges from stupa filled with paintings and sculptures to castle on mountain top and ruins of vanished kingdom. Surveying Tibetan architectural heritage hence cannot simply copy the methods from North China Plain. Although TLS (Terrestrial laser scanning) enables automated and accurate 3D measurement, it is bulky, time-consuming, and has constraints in terms of scanning radius and angle. 2D drawings based on CAD software could represent manual measurement of single building, but it is not an ideal platform representing 3D surveying results and geographical environment. Integrated use of unique ‘measured and drawn’ technologies in Tibet is necessary.

Since 2014 IRCAHC (International Research Center of Architectural Heritage Centre) of Shanghai Jiao Tong University has been engaged in surveying architectural heritage in Gyantse, a city in southern Tibet. Gyantse was prosperous as the rise of Ancient Tea-Horse Road, a corridor linking China with South Asia since Tang Dynasty. The surveying is expected to document and analyze local architectural heritage with digital technologies for potential usages such as technical intervention. This article illustrates the workflow and discusses the metric results based on a set of case studies.

2. Digital Surveying Technologies of Architectural Heritage

When choosing the surveying technology for architectural heritage, the following issues should be considered: required accuracy, object dimensions, location constraints, the instrument’s portability and usability, surface characteristics, working team experience, project budget and final goal of the survey (Remondino 2011). Optical measurement technology ensures automated and non-contact data acquisition with high accuracy. It is widely applied to surveying of large-scale and complex architectural heritage today (Rizzi et al. 2007). In the light of optical sensor types, optical measurement consists of range-based modeling and image-based modeling. Range-based modeling (e.g. laser scanning) employs active op-
tical sensor for 3D measurement directly. Having been commercialized for circa 20 years, the workflow from scanning to registration and meshing is quite straightforward today. Generally laser scanners are costly and bulky, while low cost and good portability are required in most cases. This is the major constraint hindering it from wider applications. The emerging wearable scanners and hand-held scanners are offering improved portability, flexibility and efficiency to data acquisition, but laser scanner fixed on tripod is still the most commonly type today given the factors such as scanning radius, cost and accuracy. Image-based modeling (e.g. photogrammetry and infrared thermology) uses passive optical sensor to detect light or thermal conditions of an object. Photogrammetry was applied to documenting architectural heritage even earlier than laser scanning. It recovers 3D measurement via image set photographed by calibrated camera and tie points registration among corresponding images. Conventionally both procedures, camera calibration and image orientation, require manual manipulation by skilled and experienced operators. Since a decade ago Structure from Motion (SfM) algorithms (Robertson et al. 2009) developed by computer vision community opened doors to non-expert users. SfM employs simultaneous camera calibration and image orientation, i.e. self-calibration (Pollefeys et al. 1999), to cater for automated applications. Even images photographed with different cameras, sizes and illumination conditions can be oriented via feature detection algorithms. A series open-source software (e.g. Bundler, Visual SfM, Apero) and commercial software (e.g. Agisoft PhotoScan, Pix 4D) are now available for image-based modeling. The booming of consumer-level UAV (unmanned aerial vehicle) in recent years makes low-altitude aerial image acquisition affordable and manageable to amateurs. The integration of SfM and UAV leads to promising applications such as surveying large-scale architectural heritage coupled with geographical environment. As image-based modeling relies on external reference such as Ground Control Points (GCPs) to correctly orient and scale the resulted 3D model, total station or GPS is mandatory when high metric accuracy is required. Manual survey is still useful in measuring small scale object with simple geometry such as room plan or component.

In spite of the strength of measurement technologies, the gap between data providers and data users is by no means bridged. In the light of data format, 2D drawing is still the preference of architects, architectural historians and engineers, while optical measurement outputs 3D results such as points cloud. Points cloud is a collection of huge amount points each defined by XYZ coordinates and RGB color. Although points cloud document architectural heritage with ideal accuracy and detail, the model itself is lack of semantic awareness, i.e. it is a frozen mass rejecting any modifications in common architectural software. The compromise solution is extracting a set of 2D contours from points cloud as footprints for 2D drawings. Apparently it does not take full advantage of 3D data and makes most of the on-field work redundant. Some research efforts have been put to the linkage of points cloud with BIM, e.g. HBIM (Historical BIM) (Dore et al. 2015) and as-built BIM (Barazzetti 2016). They leverage the power of BIM as a semantic-based platform with object-oriented parametric modeling. Once points cloud is transformed to BIM without the loss of geometric accuracy, further elaborations based on as-built state of architectural heritage are available such as structural analysis and
monitoring (Barazzetti et al. 2016). The current challenge is how to semantically segmenting points cloud into architectural components (e.g. column, wall, floor) with accuracy and automation. Although relevant algorithms exist (Ochmann et al. 2016), reliable and automated approach is still missed for architectural heritage given the complexity and irregularities of geometry.

3. Surveying Architectural Heritage in Gyantse

Stupas are Buddhism architecture widely spread in Tibet. As a symbolic presence of Buddha, stupas are built like a cone with reduced floors upward. Such geometry causes occlusion problems for laser beams. All the terrace floors and most walls of stupa are beyond the coverage of TLS (figure 1). In contrast, UAV guarantees a much more complete coverage with low-altitude aerial images. These images could be employed to generate 3D models in SfM software.

3.1. ACCURACY OF UAV-SFM METHOD FOR 3D OBJECTS

The unsolved issue is whether consumer-level UAV is reliable in surveying a stupa. Although positive results have been reported recently on surveying 2D objects (e.g. land, building facade) based on UAV and SfM method (Ruggles et al. 2016), the issue is much more complicated in modeling 3D objects such as a stupa. Modeling the terraces and walls of a stupa literally leads to a convergent camera network composed by both nadir images and oblique images. The two images set have different camera lens orientation, image scale, and illumination condition. Feature detection and feature correspondence of such image sets are error-prone for SfM algorithms.

The Auspicious Multi-door Stupa in Gyantse is one of the largest stupa in Tibet. It is located in Palcho Monastery which was established during AD 1418 to AD 1436 in Ming dynasty. Due to the occlusion problems using TLS, UAV-born images and GCPs measured with total station are employed for implementing image-based modeling. The employed UAV is DJI Phantom 4. The equipped camera has 12 million pixel resolution and 35mm lens (Table 1). As stated by the manufacturer, the chromatic aberration has been reduced by 56% and lens distortion had been reduced by 36% compared to Phantom 3 Pro. Both of the two factors are crucial to the quality of imaging and 3D modeling. The camera network is planned considering flight route, image coverage, lens orientation angle and GSD (Ground Sample Distance). In the end a camera network combining nadir images and oblique images with high image overlap is employed (figure 2).
A geodetic network is established with total station to evaluate the accuracy of image-based modeling. 55 evenly distributed GCPs (measuring accuracy: ±0.1mm) on each side of the Auspicious Multi-door Stupa (figure 3) are measured from 4 stations. The measurement targets are natural features (e.g. corners of painting) on the Stupa instead of commonly used print targets. The natural features are more durable and could be measured in the future for monitoring structural deformation.
The captured images are fed to commercial software Agisoft PhotoScan for automated 3D modeling. Measured targets are manually picked on the textured mesh, and local coordinates of GCPs are imported to the software to optimize the 3D reconstruction via bundle adjustment algorithms. The outputs include points cloud, texture mesh and DEM (Digital Elevation Model) (figure 4). The metric accuracy of the 3D model is also reported. It is the average accuracy reflecting the goodness-of-fit between GCPs and their corresponding locations on 3D models. The resulted RMSE is 2.05cm, 1/2000 the length (40m) of the Auspicious Multi-door Stupa. This accuracy is comparable to TLS given the potential inaccuracy of registering points cloud from many stations. More detailed evaluation is carried out by comparison with TLS-derived model (figure 5). Most points on UAV-derived model are in green indicating deviations to TLS-derived model are within ±1cm given the scalar field bar’s range is ±4cm. The large planar surfaces such as walls tend to be more accurate than brackets and moldings. This is due to UAV-derived model fails to represent the sharp transitions at such parts of the stupa. Extracting vertical sections from the TLS-derived model and the UAV-derived model, it is observed that the sharp transitions on the first model are replaced by filleted corners on the second. The accuracy assessment shows the UAV-SfM method can be a low-cost substitution of TLS in Tibet with comparable accuracy and better portability, flexibility and on-field efficiency. The accurate and complete 3D model obtained with low cost and high efficiency provide great convenience than existing research based on TLS (Wang et al. 2012) to analysis purposes such as settlement analysis (figure 6).

Figure 4. Outputs of image-based modeling.

Figure 5. Discrepancy of UAV-derived model with GCPs as compared to TLS-derived model.
3.2. INTEGRATING VARIOUS SURVEYING RESULTS IN BIM

The old town of Gyantse covers circa 70,000 square meters. The main street of the old town links the Auspicious Multi-door Stupa and the Zongshan Castle, the two most important monuments of ancient Gyantse (figure 7). As one of the last untapped living heritages even in Tibet, the residences of old town are native herds- men instead of operators of restaurants or shops. Measuring a town at such scale is beyond the capability of manual surveying, but digital technologies open doors for such demands.

The surveying was carried out in the summer of 2015. Due to the large scale and complexity of the old town, integrated surveying technologies are employed. The 3D model of old town is generated by UAV-SfM method as presented in part 3.1. The determined GSD (Ground Sampling Distance) is 5.5 centimeters which is sufficient for surveying purpose and speeds up the on-field efficiency. A hand-held Canon 5D camera captures terrestrial images of the building façade along the main street for high-definition chromatic documentation. The points cloud generated from aerial images are aligned to the ground truth model derived by TLS (figure 8). The outputs of the surveying facilitate to mapping purposes (figure 9). The orthophotography of building facade along main street with high resolution and chromatic fidelity eases the intensive manual measurement for 2D elevation.
Some of the buildings in the old town possess valuable historical information. Luocuo is a 2-story building in the old town. As former Nepalese legation in Gyantse, a room of the building is full of elegant wall paintings. The main surveying purpose is collecting comprehensive data (e.g., geometry, color, invisible hollowings) for potential technical intervention. An indoor points cloud model of the entire building is obtained with TLS from several stations. Close-range photogrammetry is employed to document the chromatic information of the wall paintings. The output orthophotography reflects detailed metric data of wall cracks.
and peeling off of pigments. An infrared thermal camera is employed to detect the hollowings beneath the surfaces which are crucial for disease analysis. The wide range of captured data requires a platform allowing multi-data management instead of conventional CAD-based drawing. A building information model is established in Revit, a commercial package of BIM (figure 10). As transforming the unstructured points cloud into parametric BIM model requires manual operation, a central issue of BIM development is distinguishing LoD (Level of Detail) according to the expected accuracy and scale. The advantages of representing surveying results in BIM consists of: 1) precise modeling based on tracing footprints of points cloud; 2) avoiding the common inconsistency among various drawings (plan, elevation, section); 3) providing access to further usages such as structural simulation.

Figure 10. Integrating various surveying results of Luocuo in BIM.

4. Conclusions and Future Development

The digital surveying for Tibetan architectural heritage is an emergent task. The last three years surveying experiences in Gyantse witnessed the vulnerability of local architectural heritage. Some of the ancient remains collapsed due to natural reasons, but the largest threat is development and construction ignoring the value of cultural heritage.

The emerging digital technologies provide opportunities to better document Tibetan architectural heritage in terms of accuracy, automation and completeness. Instead of capturing merely geometric data manually or by TLS, the integrated usages of UAV-SfM method, close-range photogrammetry, and infrared thermology allows more comprehensive data acquisition ranging geometry to color and invisible conditions. Meanwhile, such methods are low-cost and portable which are crucial factors in Tibet. The UAV-SfM method is proved to be a reliable and low-cost substitution of TLS in certain situations with similar metric quality (relative error: 1/2000). BIM-based platform serves as a central database for managing comprehensive data, and bridge the gap between raw surveying results and further data analysis and simulation for architectural history research and technical intervention.

The unsolved issues during last 3 years are mainly how to efficiently fill the gap between ‘what was measured’ and ‘what to be drawn’. Although BIM is sup-
posed to be the most ideal platform currently for such demands, it is developed for AEC industry instead of architectural heritage. It leads to a time-consuming and tedious process from points cloud to semantic-aware models in BIM. In addition, CAD drawings are still necessary for fast and preliminary surveying. GIS-based platform is useful for managing large-scale architectural heritage. Consequently, a CAD-BIM-GIS coordinated database and drawing production method for various surveying purposes and architectural types are required in future work.

Other future progresses may be addressed in the following aspects: 1) new digital surveying technologies, such as panorama camera and relevant algorithms for 3D modeling wall paintings in grotto, multispectral imaging for diagnosing wall painting and producing remotely sensed imagery coupled with UAV; 2) change detection of large-scale architectural heritage based on remotely sensed imagery over time; 3) data exchange and coordination between BIM and GIS for managing architectural heritage in various scale.

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