FROM SITE SURVEY TO HBIM MODEL FOR THE DOCUMENTATION OF HISTORIC BUILDINGS: THE CASE STUDY OF HEXINWU VILLAGE IN CHINA

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1. Introduction

The meaning of the protection of cultural heritage is self-evident and has inestimable significance for our cultural inheritance and development. Viewed as a kind of irreplaceable cultural heritage and non-renewable resource, historic buildings can also be regarded as a symbol of the cities they are part of, reflecting their cultural identities and histories. However, in the modern wave of urban construction, architecture has tended to adopt a quasi-uniform style and, as a result, has lost much of its character. In addition, historic buildings need systematic maintenance, adaptive reuse and comprehensive redevelopment, as well as interdisciplinary cooperation to protect their aesthetic, cultural and historical values. Against this background, an increasing number of modern technologies and theories have been introduced into the field of the protection and restoration of historic buildings. For example, digital technologies, such as Building Information Modeling (BIM) and Augmented Reality (AR) are being used for the virtual restoration of architectural heritage and represent an important milestone in this area.

In comparison, traditional documentation techniques, such as hand drawing, 2D photography and manual measuring with traditional devices (tapes, levels, and theodolites, etc.), cannot completely meet the requirement of reproducing the finer details of heritage artefacts with extreme precision, and may also have some negative or physically destructive impact on them [1]. In China, architectural heritage always contains numerous elements and decorations with a great many details which can easily be influenced by survey instruments. The application of 3D modelling to historical structures has therefore facilitated the observation of these finer architectural details and enabled us to view them from various distances, angles and scales. It has ultimately proved to be an effective technical support for the digital surveying, documentation, preservation and visualization of architectural heritage, and has already become a hot research topic in architecture and heritage studies [2].

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These advanced techniques have been mainly developed based on terrestrial and aerial sensing systems such as Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicles (UAV) [3]. Several studies have integrated them to achieve more accurate or complete geometric surveying for heritage modeling, digital interpretation, representation, conservation and many other issues [5]. TLS has the advantage of collecting data with higher accuracy and reducing operating time without having to touch the measured objects, thus causing less physical damage to the heritage itself. Additionally, a UAV mounted high-resolution digital camera can obtain images with high spatial resolution and high-quality 3D models but has lower manpower costs compared with other methods [6]. Being non-destructive and with these added characteristics, the application of TLS and UAV in the field of heritage protection has substantially increased.

With the development of this sensing equipment, the concept of building information modeling (BIM) has evolved significantly. BIM is not only a tool for modelling, but also provides a platform for the organization, optimization, analysis and management of information, with functions of visualization, simulation and cross-platform coordination. It has been applied to every process of architectural projects from various scales and processes, including design, construction, management, maintenance as well as the restoration of single buildings, infrastructures or building clusters [7]. The term "Historic Building Information Modelling (HBIM)" was proposed within the heritage sector as "a novel prototype library of parametric objects, designed specifically for mapping these objects onto point clouds and survey data" [8]. The general working process of HBIM starts from a digital survey, in which a set of points with defined coordinates, called "point clouds" are obtained with geometric and colorimetric information. After processing, they can be transformed into parametric smart object libraries in BIM software for further modelling. Based on the BIM model for historic buildings, the classified building components can be easily identified and analyzed for conservation purposes [9].

This paper takes some historical buildings (dragon houses) in Hexinwu village as a research subject using HBIM as the main methodology. The aim is to introduce these digital technologies into the protection of historical buildings in Chinese traditional villages. This multiple survey method, including data processing, presentation and documentation, focuses on the integration of TLS and UAV photogrammetry to acquire rapidly comprehensive data of the diverse elements of the historical buildings. The TLS is used for data acquisition of the building facades, while the UAV is used for scanning the roof parts. Furthermore, the process of dealing with point clouds and building parametric objects in BIM is discussed. Finally, the built model, based on the fine point cloud data, is an important update in the documentation of Hexinwu village. In addition, the visualization of heritage in 3D/AR/VR format is also beneficial for heritage tourism and further research. Thus, this project is not only useful and meaningful for the future planning of the protection of Hexinwu village, it can also be a reference for other Chinese architectural heritage with complex decorations and complicated spatial compositions, such as the traditional ancient Chinese courtyard used in residential compositions in Beijing, as well as in other temples and palaces.

2. Study area

Hexinwu village (24.228836° N, 114.819558° E) is located in Dahu town, Guangdong province in Southern China (Figure 1), which is the birthplace of the Hakka culture (a branch of Chinese culture in the south of China), and where there are a number of important historical Hakka villages. Some archaeological relics (land lease documents from the Qing Dynasty) have already been found in Hexinwu village, but the village has not yet been included in the national list of historical villages, and its current status of protection is not optimistic.

This study focuses on a cluster of ancient Chinese buildings in the center of this village, which covers an area of nearly 3000 m^2. As one of the most typical historical villages composed of dragon houses with Chinese architectural characteristics, Hexinwu village was originally built during the period 1368-1644 because of its convenient location near the post road in Guangdong. It was enlarged several times by a family named “HE”, a eunuch family, in the late 19th century. With a history of more than 300 years, the central buildings in the village serve as the ancestral houses of the HE family, which are enclosed by wall-structures composed of two semicircles. The front half of the circle is a crescent fishpond and the other half of the circle is the residential house, which symbolizes the shape of coiling dragons, and thus they are called “dragon houses” (Figure 2). Historic buildings in Hexinwu village combine artistic values with practical functions. The main halls serve as spaces for ritual or other traditional activities, with the front hall housing the ancestral shrine of the family [10].

Unfortunately, due to the rapid population growth, urbanization, pollution and modernized lifestyle in Guangdong, the survival of the existing buildings in this village is threatened. Some of the buildings at the edge of the village have already been destroyed, while others have been partially damaged and can no longer be used. But the central houses still function as residential buildings for locals, and these are the main survey objects in this study. The other buildings outside the central area have not been taken into consideration.

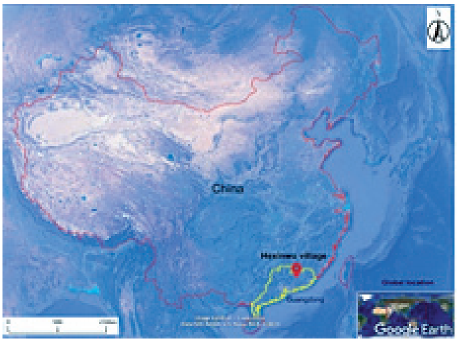

Figure 1. Location of Hexinwu village in China.

Figure 2. (a) Study area; (b) site photos.

Nowadays, Hexinwu village is facing great danger because of the current situation. However, despite their great value and importance, these dragon houses are seldom studied by Chinese scholars. The government of Guangdong, jointly with the University of Guangzhou, is currently trying to survey, record, protect and restore this traditional village. A comprehensive survey to assess the current condition of the historical buildings and a conservative strategy for the whole village are badly needed.

3. Methodology

The whole research process can be classified in five steps (Figure 3). The first step was to determine the survey plan. Then, the TLS was introduced to scan the facades of the village, while the UAV was used to capture photos to eliminate the occlusions from the TLS survey, mainly the roof parts. In order to achieve rapid and comprehensive data collection, a flight plan for the UAV was designed and carried out and the TLS scan positions were settled to cover the entire study area with the minimum number of scan positions and aerial photos. Then, the raw data of the two methods were processed to get two individual point clouds (TLS point cloud and UVA point cloud). After using the common reference of these point clouds to assist the fusion (registration) of the TLS and UVA, the HBIM model of the central dragon houses in Hexinwu village were obtained and were ready for further analysis and applications.

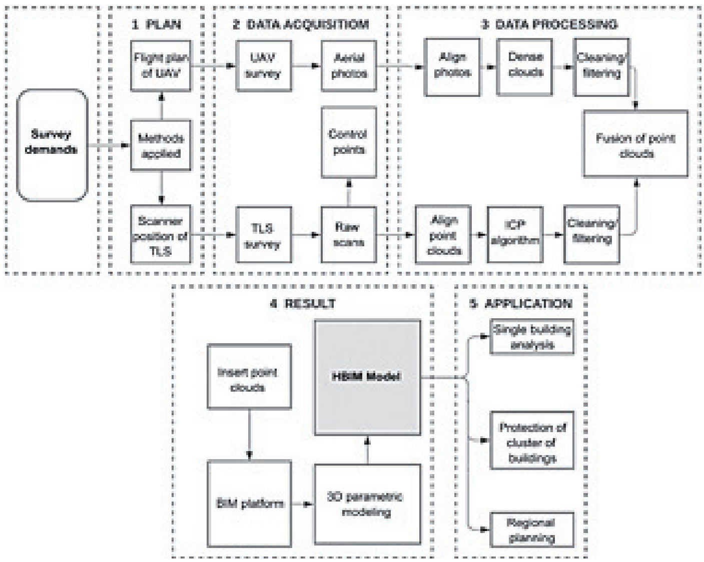

Figure 3. Workflow in this study.

3.1. Data acquisition with terrestrial laser scanning

The digital tools (TLS and UAV) make data collection in this project fast and comprehensive. For the terrestrial scanning of the dragon houses, a 3D LiDAR scanning instrument called Trimble TX8 was employed (Figure 4a). In general, a LiDAR emits laser pulses for measuring distances, obtaining information about the texture of the building materials and their degradation. A TX8 scanner has a scanning range of 120 meters, a 360° (horizontal) and 270° (vertical) field of view and it can capture scans at a speed of up to 1 million points/sec. Compared with other tools, the main characteristics of this scanner are its high precision, high resolution, high speed and the fact that operating times are reduced and it has no destructive effects on the objects under examination. In addition, it is integrated with a digital color camera, and during the scanning process, can obtain images with RGB color information and a capacity of 1920*1920 pixels [11].

Figure 4. (a) The Trimble TX8; (b) The scanner positions and field-of-view.

The whole site was surveyed by TX8 from a total of 35 scan stations. The positions of the scanner are showed in Figure 4b, considering that there is enough overlap (more than 40%) between every two consecutive scans. Furthermore, a side overlap of 30%-50% between the adjacent scans ensures an accurate 3D point cloud model [12].

3.2. UAV

Due to the limitations in height of the TX8 scanners, the roofs of the buildings could not be well recorded. For this reason, a UAV was employed as a low altitude aircraft, and introduced as a supplementary tool for the laser scanning to produce images from different views. The UAV is a flexible, low-cost, high frequency tool, equipped with a high-resolution camera and a GPS device, which generates diverse types of geographical products and highly detailed models [13]. For this aerial survey, a DJI Phantom 4 Pro was used and is a photography drone designed by Da-Jiang Innovations in China, with an onboard camera equipped with a 1-inch 20-megapixel CMOS sensor and an FOV 84° 8-mm lens. The Phantom 4 also has a GPS device and optical recognition system. This combination facilitates further photo alignment in later processing.

In order to acquire more detailed images of Hexinwu village, two different types of flight plans were combined. The first one with a nadiral configuration of the camera and the second with an oblique configuration [14]. Each type of flight ensured an overlap between consecutive photos of at least 70% (Figure 5). The speed of flight was nearly 1.5m/sec and the average flight altitude was 25m; the lens covered an area of approximately 4 hectares with one photograph, with an image resolution of about 3 cm/pixel. The detailed flight parameters, including the records of flights, type of drone, sensor, number of photos, etc. of both flights are shown in Table 1. For the study site, a total number of 775 photographs were taken.

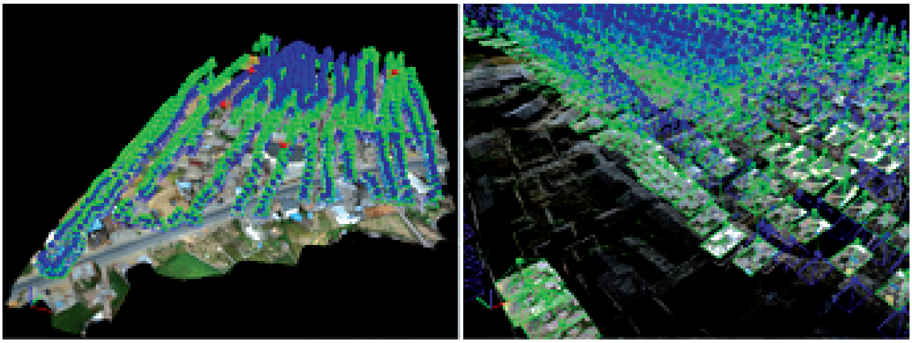

Figure 5. Flight path of the UAV.

Table 1. UAV flight specifications

Flight date	2019/11/03	2019/11/04	2019/11/05
Duration	20 mins	22 mins	25 mins
Altitude	25 m	25 m	25 m
UAV type	Quadcopter	Quadcopter	Quadcopter
Optical sensor	DJI	DJI	DJI
Resolution	3.64 mm	3.64 mm	3.64 mm
Dimension	6.3 * 4.7 mm	6.3 * 4.7 mm	6.3 * 4.7 mm
Pixel	1.55 μm	1.55 μm	1.55 μm
FOV direction	Nadir	45°	45°
GSD	0.56 cm	0.56 cm	0.56 cm
Number of photos	300	255	250
Distance	200 m	220 m	250 m

3.3. Pre-processing of point cloud

The point data acquired from the TLS and UAV need to be preprocessed independently to form the point cloud in different software due to their different characteristics. The pre-processing stage can be divided into two sections: in the first, the data collected from the scan positions using TLS were processed with "Trimble Realworks", provided by Trimble, for transforming the scan data into 3D deliverables, as well as "Autodesk Recap", designed by the Autodesk Company with tools for systems integration, workflow optimization and BIM modeling; in the second, the UVA photos were processed by Photo Scan Pro software, which performs the photogrammetric processing of digital images and generates 3D spatial data.

In Trimble Realworks, multiple scans were imported with appropriate positions connected to each other according to their respective coordinates. After converting the point format into E57 (a compact and vendor-neutral format for storing point clouds), they were loaded into the Autodesk Recap. The cloud-to-cloud registration technique was applied, which did not need any targets but only point clouds aligned to each other by extracted features within the overlap area of each point cloud. After registration, the color of the point cloud data was also captured by the integrated digital camera (Figure 6) [15]. Due to an overlap between pairwise scans (>40%), the registration of TLS data produced a dense point cloud. As a result, this point cloud had a spatial resolution of 1 cm and was registered with the 3 spherical target references. The average error of registration point was 2.0 mm and the maximum error was 3.5 mm.

The data captured with the UAV were imported into the Photo Scan Pro software for automatic processing, including aligning photos, optimizing alignment and building dense clouds. The processing algorithm was based on the Structure from Motion method (SfM). and is a photogrammetric method for creating 3D models of features from overlapping 2D photographs taken from different positions and orientations to rebuild the scenarios. In this process 500,758 tie points were found. The median reprojection error was 0.21 pixel and the root mean square (RMS) of reprojection errors was 0.51 pixel. The output of the UVA point cloud is shown in Figure 7.

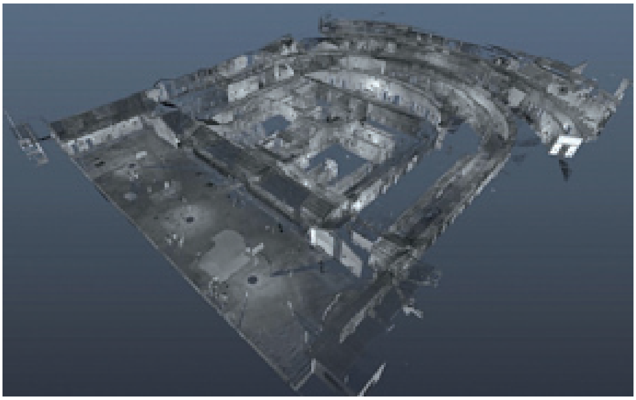

Figure 6. Point cloud of east side of buildings.

3.4. Integration of point clouds

The combination of the UVA and TLS point clouds make up a whole. Obviously, the UAV flights captured the top view of the buildings because of the height of its sensors, while the TLS tool scanned the side view of the buildings. The parts of the roof captured by the UAV, restored the data missing from the TLS. By combining the two sets of data, a complete data model of the whole building area was produced. Thus, the two individual point clouds of TLS and UAV were processed to integrate them. Merging the two individual point clouds was conducted using the Iterative Closest Point algorithm (ICP), an algorithm to minimize the difference between two point clouds. It includes repeatedly matching the closest point in the reference and estimating the minimum translation, to transform the source points and re-associate them. The final product is an accurately dense 3D point cloud of the historical buildings in the center of Hexinwu village, containing detailed information of both the top view and side view of the houses (Figure 8).

Figure 7. Point cloud of roof parts.

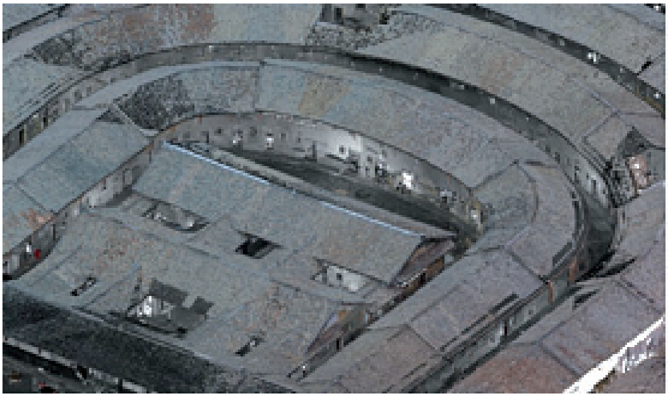

Figure 8. Aerial view of the integrated point cloud from TLS and UAV.

4. Modeling in BIM

Unlike other cultural relics, ancient Chinese buildings have the characteristic of being large in size and having a complex structure with an abundance of details. Generally speaking, a single Chinese building can be composed of dozens to hundreds, or even thousands of components or elements. In BIM, building information is considered directly as the management object, and building components are basic geometric units. Each type of component corresponds to one "family" group (a method of classification). Because of the same architectural style and structure of the houses in the village, the rule for classifying the building components of the dragon houses is according to their position and geometry in this project. For example, the doors, windows and walls of the houses can be regarded as a family of "retaining structures"; the building of these "families" was finished before the BIM modelling process started. Finally, the models of all the families were assembled as a complete building, using a structure called "scaffolding" to organize all the families. Additional features can be attached to the model of the building components, such as structure, composition, material, shape, quality, size, color and so on, which will serve for further architectural analysis. The whole parametric BIM modelling workflow of dragon houses in Hexinwu village can be summarized as shown in Figure 9:

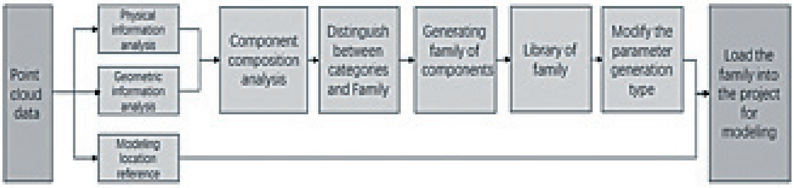

Figure 9. HBIM Modeling process.

According to the finished site survey, the wooden structure of dragon houses is not complicated. Using the analysis of all the built point clouds, the architectural components of the Hexinwu houses can be classified into four families, namely foundation, wood structure, retaining structure and roof. Each building component can be viewed in BIM and coded by ID numbers, for example, the window components are listed as W_1, W_2, etc. After distinguishing the difference among these components, the component families and their further subclassifications are shown in Figure 10.

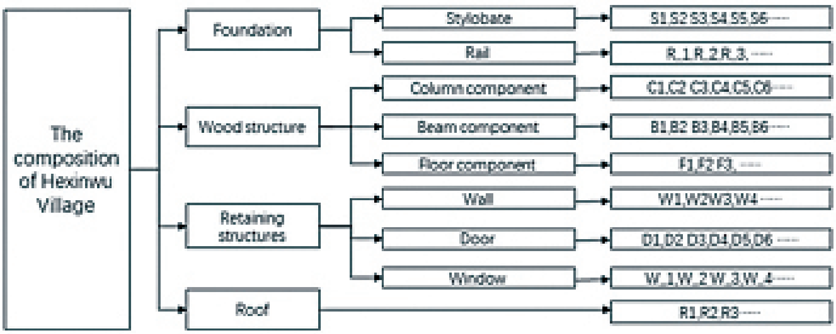

Figure 10. Architectural components of dragon houses.

Afterwards, a library of corresponding parameterized components was established. Point cloud data provides accurate geometric data for the "family" models of the building components. Ancient Chinese buildings have a modular scale and characteristic combination involving a "parameterized" design and construction process, based on specific components. For example, the pillars in every house in Hexinwu follow the same module. Establishing a parametric family model and setting the main driving parameters can standardize the shape and scale of every component in the houses. "Revit" (a professional BIM software) allows each family object to be assigned several attributes related to its geometrical structure, composition and other properties.

In the last step, each family was fitted into the appropriate position in the BIM model using a "hosting" technique [16]. In the case of the dragon houses in Hexinwu, each main wall of the structure was considered as a "host" of the modelled family; each family was, therefore, manually placed in the wall according to its position in the point cloud. The final BIM model is illustrated in Figure 11.

The resulting HBIM model is a data-rich, object-oriented, intelligent and parametric digital representation of the dragon houses in Hexinwu village. This makes all the information (views and data) on Hexinwu easily available and can appropriately meet the various needs of its users. It can also be extracted and analyzed to generate information to make decisions and to improve the process of preservation of architectural heritage in the future [17].

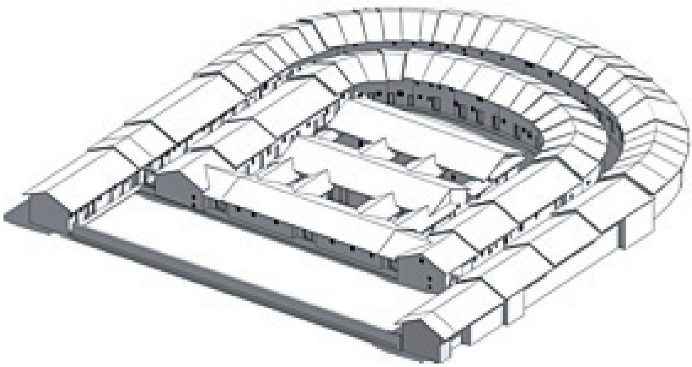

Figure 11. Final HBIM model of Hexinwu village.

BIM models, moreover, follow the principle of "information interoperability". The data format provided by BIM is an international structured form and proper standard data format – IFC (Industry Foundation Classes). Developed for the exchange and sharing of building information during projects, the IFC provides open data file formats about architectural, building and construction information and is widely recognized by many international companies working in these fields. With the uniform IFC model, different software environments share the same data standard, and the building information can interact in various environments [18]. Thus, the built HBIM model of Hexinwu village can be easily shared with other scholars for further studies.

5. Conclusion

In this study, Hexinwu village, one of the most famous and important ancient Hakka villages in China, was taken as an example to describe the process of digitally documenting Chinese architectural heritage, from the initial use of multiple site-survey techniques to the final HBIM model. The study describes how precise surveys were made and documentation was produced using scanning technology, i.e. the TLS and UAV systems. Survey methods included various techniques, such as data acquisition, data processing, data integration and appropriate presentation. Generation of the HBIM model was obtained starting from collected point clouds, point clouds from laser scanning and UAV data, to build a detailed HBIM model. HBIM has demonstrated its ability to capture and record information related to heritage building. It is therefore not only useful for the presentation of the Chinese traditional village, but also shows potential in its application to other cultural heritage contexts with complex components.

The HBIM model will provide critical information for the protection of ancient buildings and the inheritance of traditional architectural heritage. For example, from the scale of single heritage building, the internal environment (solar and wind analysis, etc.) can be stimulated along with other geographic data; from the scale of the village, the spatial arrangement of building clusters can be evaluated and analyzed in a Geographic Information System (GIS) environment; and from a regional scale, future tourism and heritage protective planning can be proposed according to the HBIM information [20].

With thdevelopment of computer technology, related digital technologies will become even more sophisticated. In the foreseeable future, more digital technologies such as 3D printing, big data, AR/VR can be used in different combinations as methods for the digital protection of heritage. Nevertheless, more systematic research needs to be done to contribute to a more comprehensive digital construction of architectural cultural heritage.

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Summary

Architectural heritage surveying plays a fundamental role in the preservation of historic buildings for scientific research, education and tourism. The use of Unmanned Aerial Vehicles and Terrestrial Laser Scanning techniques are essential for architectural heritage surveying and mapping. In recent years, the combination of Building Information Modelling (BIM) with heritage studies has been presented as Historic BIM (HBIM) which, integrated with UVA and TLS, is a technique that is able to deal more efficiently with the management and protection of historic buildings. This paper focuses on the integration of UVA images and point clouds from laser scanning to build a 3D architectural model for the documentation of Chinese historic buildings. In particular, the method, tested in the case study of the traditional village, Hexinwu, China, can contribute further to the analysis, evaluation and heritage planning of this remarkable architectural structure, thus increasing its historical significance for the future.

Riassunto

Il rilievo del patrimonio architettonico è fondamentale nella conservazione degli edifici storici per la ricerca scientifica, l'istruzione e il turismo. L'uso dei veicoli aerei senza pilota e le tecniche di scansione laser terrestre sono essenziali per il rilevamento e la mappatura del patrimonio architettonico. Negli ultimi anni l'abbinamento del Building Information Modeling (BIM) con gli studi sul patrimonio è stato presentato come Historic BIM (HBIM) che, integrato con UVA e TLS, permette di affrontare in modo più efficiente la gestione e la tutela edifici. Questo documento tratta l'integrazione di immagini UVA con l'insieme punti scansionati con laser per costruire un modello architettonico 3D per la documentazione di edifici storici cinesi. In particolare, il metodo testato nel caso di studio del villaggio tradizionale, Hexinwu, Cina, può contribuire ulteriormente all'analisi, valutazione e pianificazione del patrimonio di questa straordinaria struttura architettonica, aumentando così la sua importanza storica per il futuro.