PARAMETRIC H-BIM FOR CHINESE HISTORICAL ARCHITECTURES BASED ON ANCIENT DESIGN PRINCIPLES AND 3D RECONSTRUCTION TECHNOLOGIES

Xinyu Tong[1], Cheng Zhang[1]*, Yiping Dong[2], Yue Li[3]

ABSTRACT

Heritage Building Information Modelling (H-BIM) integrates the physical and functional characteristics of historical architecture into a digital representation, promoting sustainable management of the protection, restoration, and dissemination processes. However, due to the unique and complex geometry of Chinese historical architectures, creating an H-BIM model with comprehensive information is challenging. Conventional "3D reconstruction-only" models only contain surface information, and the current parametric modelling cannot reflect existing historical architectures in reality. To address the challenges, the present paper integrates parametric modelling and 3D reconstruction to fit the existing Chinese historical architectures. Based on the ancient design principles in *Ying-zao fa-shi*, a procedure is proposed for the efficient generation of various parametric components and the whole model. The obtained model encompasses both exterior and interior information of the architecture with a very small deviation from the existing architecture. Furthermore, high-resolution images are mapped onto the model as texture, allowing the model to reflect the defect information. Additionally, the strengths of photogrammetry and laser scanning are combined to achieve complete and accurate data acquisition. A case study was carried out at Pan Gate, China, where a complete parametric model was generated through the fusion of multiple data sources and parametric modelling. The model accurately reflects the actual architecture and enables further site management tasks, such as structural analysis and defect inspection.

KEYWORDS

Chinese ancient architecture, Parametric procedural modelling, Heritage BIM, 3D reconstruction, Design principle

INTRODUCTION

Historical architecture is a witness to human society's development and carries a country's culture. Conventional methods for the protection, restoration, and dissemination of historical

---

1. Department of Civil Engineering, Design School, Xi'an Jiaotong-Liverpool University, China.
2. Department of Architecture, Design School, Xi'an Jiaotong-Liverpool University, China.
3. Department of Computing, School of Advanced Technology, Xi'an Jiaotong-Liverpool University, China.

DOI: 10.3992/jgb.21.2.313
URL: https://doi.org/10.3992/jgb.21.2.313

architecture mainly rely on fragmented historical texts and photographs. However, the lack of comprehensive and systematic handling of relevant documents hampers the accurate and efficient retrieval of valuable information, resulting in unsustainable management that wastes time and costs, which is prevalent in many heritage sites (Penttilä et al., 2007; Tomaževič et al., 2007, Gursel et al., 2009). Therefore, developing and introducing resources and tools to support relevant personnel in their management is strategic.

Under such requirements, Heritage Building Information Modelling (H-BIM) has gained increased implementation in heritage sites, which is a technology that digitally integrates the physical and functional characteristics of historical architectures into 3D models (Suermann & Issa, 2009; Li et al., 2017; Pocobelli er al., 2018; Simeone et al., 2019). The concept of H-BIM was first proposed by Murphy (2009) as a system for modelling historical structures using BIM. H-BIM serves as a comprehensive and coherent information database and assists relevant personnel in the protection, restoration, and dissemination of cultural heritage. It integrates relevant information of the architecture such as the geometry, material, component type, craftsmanship, defect status, etc., which addresses the problem of inefficient project management caused by a lack of documentation in maintenance processes. Additionally, H-BIM ensures that information is preserved for restoration or reconstruction in case of damage from natural or accidental causes (Chandel et al., 2022) and enables the dissemination of historical knowledge to audiences through virtual museums (Gomes et al., 2014).

Generating an accurate as-built H-BIM model for historical architectures is challenging in situations such as the unavailability of preserved documents, unreliable original drawings because of construction discrepancies during the ancient working process and subsequent renovations or damages over time. Therefore, it is necessary to obtain data from the actual architecture and utilise reverse modelling techniques to develop an as-built H-BIM model, which is known as 3D reconstruction. 3D reconstruction has been widely applied in the surveying of historical architectures, prompting the digitisation and visualisation of the heritage site. The preparatory work before the 3D reconstruction modelling process is data acquisition, where spatial information of architectures is collected without secondary damage through photogrammetry or laser scanning technologies, which has higher accuracy and efficiency compared to conventional surveying techniques (Soleymani et al., 2023; Santos et al., 2023). Subsequently, these collected data undergo a series of processing procedures to generate the final actual model. However, photogrammetry and laser scanning only capture surface information, for that reason the model generated by conventional data processing method only encompasses the appearance of the architecture, but does not cover the interior information. Therefore, parametric modelling is introduced as a supplement method to enrich the exterior and interior information of H-BIM.

Parametric modelling is built upon the concept of linguistics, referring to representing new geometric shapes through transformations and combinations of basic geometric shapes (Sutherland, 1968). Architectural design principles are taken into consideration and parameters such as the geometry, size, and positional relationships are incorporated when creating the parametric model. Compared to conventional data processing models, parametric models contain not only interior information but also more semantic information, enabling the representation of the functionality of the components, which is beneficial for the sustainable management of historical architectures (Chiabrando et al., 2018; Radanovic et al., 2020). Furthermore, parametric modelling offers higher flexibility as adjustments can be made by modifying the corresponding parameters without the need to redraw the entire model, which improves the efficiency of the modelling process (Massafra et al., 2020). However, as the parametric design procedure is conceptual, parametric models still cannot effectively represent localised irregularities or imperfections in the existing historical architecture.

The paper presents solutions to address various challenges in modelling complex historical structures and components. Parametric modelling is introduced for creating H-BIM of Chinese historical architectures, an efficient procedure is proposed to generate the components by drawing references from Chinese ancient design principles. Combining with advanced 3D reconstruction technologies, such as photogrammetry and laser scanning, the study achieves precise modelling of the exterior and interior structure, and more comprehensively reflects the characteristics of Chinese historical architecture, contributing to providing a reliable foundation for subsequent research and management processes in the field of historical architectural studies.

TECHNICAL BACKGROUND

Data Acquisition

Data acquisition is a preparatory work for 3D reconstruction. Photogrammetry and laser scanning are two data acquisition technologies with distinct formats. The accurate and comprehensive data ensures that the architectural information is not lost during the modelling process. Therefore, understanding the characteristics of the two technologies is essential for effectively utilising them to collect data as complete as possible.

Photogrammetry entails the capture of a series of contiguous images, accompanied by internal parameters and positional information in the camera. Through image alignment algorithms such as Structure from Motion (SfM), feature points are identified in the overlapping regions of adjacent images. These images are then aligned in 3D space to create a comprehensive model. Due to the algorithm's dependence on feature points, in order to ensure high image registration accuracy, the minimum overlap should be set to 75% or more between adjacent photos. It is also recommended to avoid extreme luminosity conditions and minimise the duration of the capture process, thereby ensuring consistent lighting conditions across all images. Camera is often mounted on unmanned aerial vehicles (UAVs) for large-scale surveying, owing to its inherent portability (Vlahakis et al., 2001; Huo et al., 2020; Microsoft, 2021).

Laser scanning is another data acquisition technology based on laser ranging. It captures a vast amount of 3D coordinate information from densely surface points to reconstruct the 3D model of the measured object. Laser scanning is widely used for the precise surveying of many heritage sites because of its high scanning accuracy (Pesci et al., 2011; Böttger et al., 2016; Balado et al., 2022). Due to the limited scan range and angle of the terrestrial laser scanners (TLS), a single scan station cannot acquire a complete dataset encompassing the entire architecture. Therefore, multiple stations are typically set up for scanning. The point cloud data obtained from each station exists independently in multi-viewpoint coordinate systems, which need to be spliced and unified to obtain comprehensive spatial information about the architecture. This process works by finding common points in the overlapping scanning region from adjacent scan stations. By manually placing three or more non-collinear targets as common feature points between scan stations, the point clouds can be integrated simply with reliable results.

Photogrammetry and laser scanning have their respective advantages and disadvantages, as shown in Table 1, based on previous research (Aicardi et al., 2016; Surový et al., 2016; Liu & Wu, 2019; Huang et al., 2021). In general, UAV photogrammetry covers larger areas and captures the original colours of the heritage, but it is susceptible to external environmental factors. On the other hand, terrestrial laser scanning is more precise but has a smaller scanning

TABLE 1. Comparison of Photogrammetry and Laser-scanning Method.

Photogrammetry	Laser Scanning
• Real texture, original colour; • More sensitive to environmental conditions (such as illumination conditions, wind, etc.) • Relies on identifiable features (control points), vague features may lead to misplaced points; • Cover larger areas, useful for acquiring immediate accurate information for large-scale objects.	• Less noise and clutter; • Is able to penetrate through semi-transparent objects (such as tree canopy); • More precise measurement → Obtain more details; • Unstructured point cloud, unevenly distributed data; • Only pointwise sampling, • High cost and low portability

range and lower portability. Therefore, it is necessary to combine these two methods to collect data completely, accurately and efficiently.

Parametric Modelling for Historical Architectures

Murphy (2009) pioneered parametric modelling for the reconstruction of Western historical architectures, using design principles derived from ancient manuscripts to construct parametric representations of architectural components, then establishing parametric library elements and finally mapping these elements onto the point cloud, which not only improved the efficiency but also enriched the semantic information in the model. After Murphy, parametric modelling has been used to address the difficulties in modelling historical architectures. In data acquisition of actual architectures, external factors such as lighting, shades, and difficulties in reaching certain shooting or scanning positions due to complex terrain can result in low accuracy, loss of details, or even missing data. By generating parametric components based on design principles and combining them with the actual model (the mesh model solely from 3D reconstruction), the actual model can be supplemented and improved (Dylla et al., 2010). Additionally, historical architectures have unique styles with complex geometries, which brings many difficulties to the modelling process. By establishing a parametric library of components, when encountering components of the same style or type, they can be directly retrieved from the library and mapped onto the corresponding locations in 3D space after adjustment, which reduces the repetitive modelling process (ElWahab et al., 2019).

One of the challenges faced by parametric modelling is the generation of complex components. Several studies tried to derive parametric elements from the collected data, but only for components with simple flat geometry whose structures are easy to identify, such as lintels (Chevrier et al., 2010) and façade (Haegler et al., 2010; Dore & Murphy, 2013). For historical components with high level of irregularity and unique shapes, the most used method is creating a Non-Uniform Rational B-Spline (NURBS) surface by fitting knots and curves to a point cloud and then importing the surface into the model (Barazzetti, 2016; ElWahab et al., 2019; Costantino et al., 2023). However, it is important to note that NURBS does not reflect the specific design principles of architectures that the fitted curves are irregular and completely computer-generated, and they only fit a specific element. It is not parametric in a way that enables fast and efficient model updates, if the proportion or position of structural elements need changed or another element needs to be fitted, the entire procedure must be repeated, which defeats the purpose of parametric modelling (Radanovic et al., 2020).

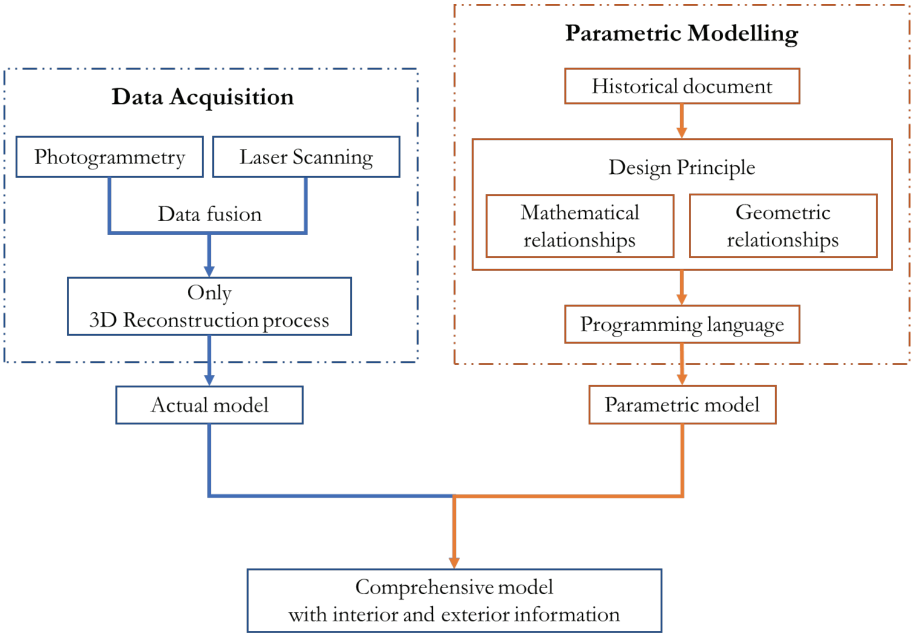
The second challenge is that current parametric models often cannot reflect existing historical architectures in reality. This is because they are typically standardised, generated according to specific rules. However, existing historical architectures often deviate from conceptual designs due to errors in manual construction, as well as subsequent damage and restoration. How parametric models can accurately reflect real, existing historical architectures has been less studied.

For Chinese historical architectures, the intertwined structures, as well as complex and closely interconnected components, pose challenges in both data acquisition and parametrical design for the 3D reconstruction of H-BIM (Liu, 2018; Liu et al., 2019). These challenges result in insufficient data collection and a lack of a specific parametric library for the components. The current parametric modelling of Chinese historical architectures is limited to simple structures, separated component or relying on the NURBS method (Liu et al., 2019; Shen et al., 2021; Hu & Qin, 2021). To address these challenges, the following section proposes an improved method for data acquisition and expands the application of parametric modelling to better reflect Chinese historical architectures, including a setting scheme for data acquisition of historical sites using multiple data sources, and a parametric programming workflow derived from Chinese ancient design principles.

METHODOLOGY

As shown in Figure 1, the Methodology for creating parametric H-BIM involves data acquisition and parametric modelling. Data acquisition is the preparatory work before the modelling process, where photogrammetry and laser scanning are utilised to capture the surface data of the actual architecture. The two sources of collected data are fused to generate the actual model, which is a model solely derived from photogrammetry and laser scanning-based 3D reconstruction process that used as a reference for mapping on parametric elements. Parametric modelling

FIGURE 1. Proposed Methodology.



is employed for 3D reconstruction data processing to efficiently construct a comprehensive parametric model which includes both exterior and interior information of the architecture.

Multisource Data Acquisition and Data Fusion

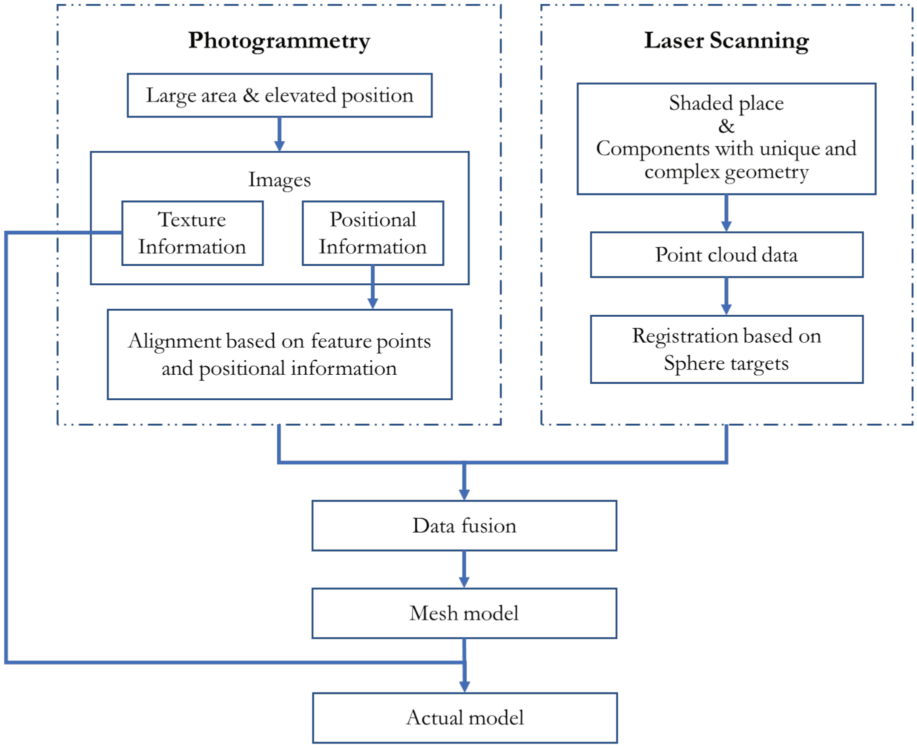
Many historical architectures have large areas or elevated heights, the collected data should cover the whole parts of the sites. The architectures also contain components with unique and complex geometries, which means that the collected data should be accurate for better identification of them. Therefore, photogrammetry and laser scanning are combined and complement each other to meet these data acquisition requirements.

As shown in Figure 2, UAV photogrammetry is used to cover large areas and access elevated positions, also providing texture information. At the same time, laser scanning is employed to capture the unique and complex shapes of components accurately. Images are aligned based on the feature points and positional information, while laser point clouds are registered based on the targets. After that, data from these two sources are fused for the 3D reconstruction process and the mesh model is generated. Finally, textures are mapped onto the mesh to get the actual model, a model solely reconstructed from image and laser data, which reflects the appearance of the actual architecture.

Parametric Modelling Based on Chinese Ancient Design Principles

For Chinese historical architecture, a series of specific design principles can be found in historical documents, such as *Ying-zao fa-shi* (Li Jie, Song dynasty) and *Gong-cheng zuo-fa ze-li* (Qing dynasty), which are standards issued by the imperial court; *Qing-shi ying-zao ze-li* (Qing

FIGURE 2. Data Acquisition Process.



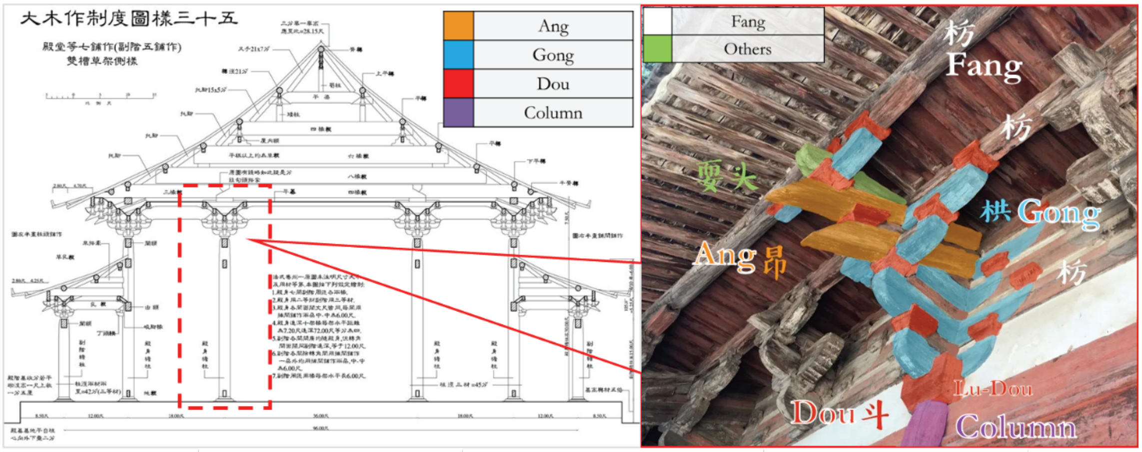
structural regulations), written by Liang Sicheng in 1934; *Ying-zao fa-yuan*, written by Yao Chengzu in 1986, recording historical architectures in the provinces south of the China. These documents provide an understanding of the ancient architectural terminology, construction techniques, and structural details of the historical architectures. From these grammar books, it is understood that the components are not manufactured randomly. The design principles can be extracted from ancient manuscripts and converted into digital representations through the following procedures.

Basic Parameter

Certain proportional relationships among the dimensions of the components can be found in the design principles, which were formed during the development of Chinese historical architecture. In the Song Dynasty, one of the proportional relationships is called the *Cai-Fen system*. *Ying-zao fa-shi* defined eight grades of standard timbers with 3:2 rectangular cross-sections called "*Cai*." The depth of each *Cai* is divided into 15 segments, called "*Fen*" (Figure 3). *Ying-zao fa-shi* stipulates that every dimension in the architecture is to be measured in terms of *Fen* of the grade of *Cai* used, which means the specifications of a house and the size of the components are all measured in *Fen* as the minimum unit. Therefore, as long as the basic size parameters *Cai* and *Fen* are defined, other size parameters of each component can be derived.

Take the structural carpentry as an example (Figure 4, left), which is a major part of the Chinese historical architectural system and serves as the framework for wooden structures. In

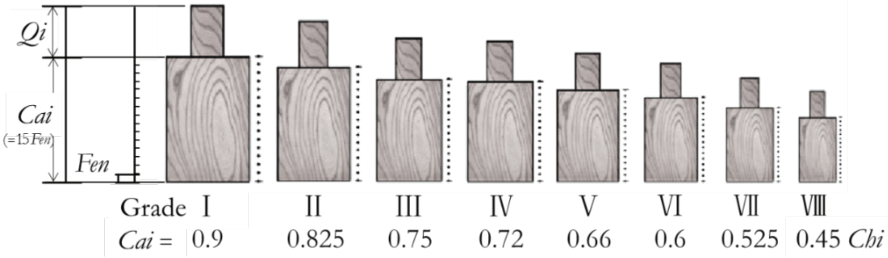
FIGURE 4. The *Cai-Fen System* and Components which form the Structural Carpentry.



Structural Carpentry

Column Bracket Set

FIGURE 3. Grades of *Cai* and *Fen*.



actual historical Chinese architectures, the construction of the structural carpentry is the most consistent with the requirements of the *Cai-Fen system*. The bracket set, as known as Dou-Gong, is the most complex part of structural carpentry, which consists of interlocking Lu-Dou, Gong, Fang, and beam components (Figure 4, right), supporting the roof and eaves and transferring the weight to lower structures such as column. Table 2 lists the dimensions and positional relationships of some components involved in the bracket set of structural carpentry, indicating that most components are measured in "*Cai*" and "*Fen*" and adhere to strict geometric relationships. In the following sections, these components which are based on the *Cai-Fen system* will be used as examples to elucidate the mathematical and geometric relationships for the generation process of the models.

Mathematical Relationships

Based on the *Cai-Fen system*, the basic parameters *Cai* and *Fen* can be defined, and their mathematical relationships with other dimensions can be described under certain procedures. This allows for the quick generation of digital representations for all dimensions derived from the basic parameters in the program. Taking Lu-Dou, the sub-component of the bracket set Dou-Gong, as an example, once the grade of *Cai* is deduced from actual architecture, then the minimum unit *Fen* is obtained as 1/15 of it. Through proportional calculations, a series of related dimensions can be derived, for example, "Dou-Er," "Dou-Ping," and "Dou-Qi" are respectively 8 times, 4 times, and 8 times the unit *Fen*. This computational process is shown in Figure 5.

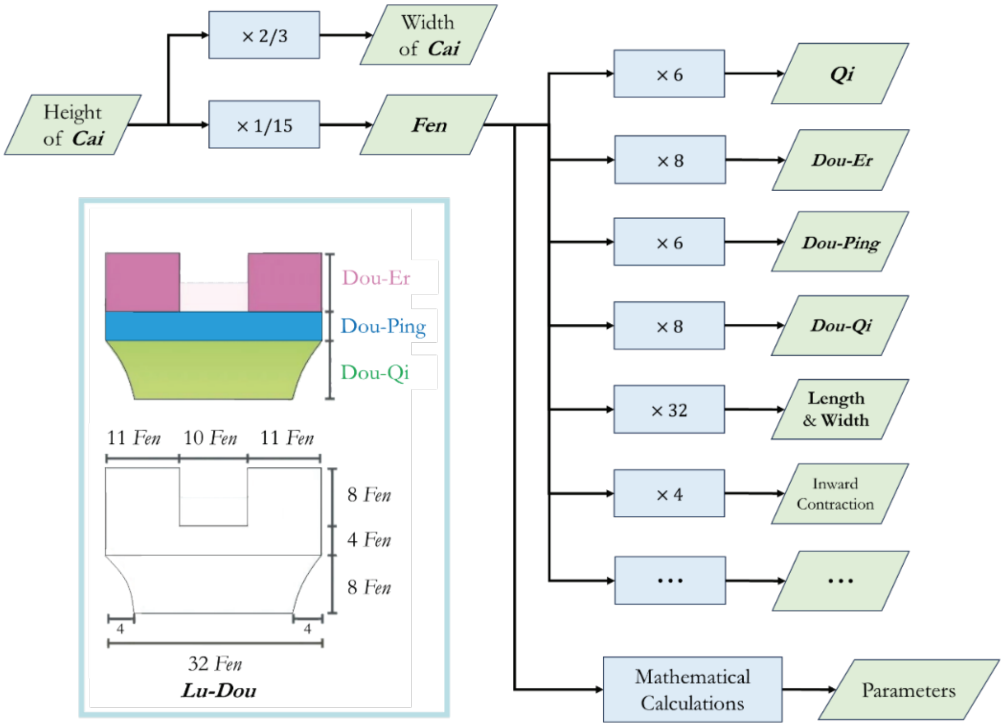
Geometric Relationships

The geometric relationships outlined in design principles can also be represented under certain procedures. Taking the generation process of the column geometry as an example, Chinese ancient columns are typically not straight cylinders but have a shuttle shape at the top, known as "Juan-Sha." According to *Ying-zao fa-shi*, Juan-Sha is positioned at the upper one-third of

TABLE 2. Components of a Column Bracket Set.

Level	Component	Dimensions	Positions
From top to bottom	Ang	The length is generally 23 ***Fen***	Inclined within the bracket
	Ni-dao Gong	The length is 62 ***Fen***	On the Lu-Dou
	Hua Gong	The length is 72 ***Fen***	On the Lu-Dou
	Lu-dou	The length and width are generally 32 ***Fen***, and the height is 20 ***Fen***. Dou-Er is 8 ***Fen***, Dou-Ping is 4 ***Fen***, Dou-Qi is 8 ***Fen***.	On the column
	Column	Diameters are varied from 2*Cai* 1*Qi* to 3 *Cai*; Juan-Sha is a 4 ***Fen*** inwardly tapering	On the floor
	Fen	1/15 depth of *Cai*	
	Cai	Eight grades of standard timbers defined in *Ying-zao fa-shi*	

FIGURE 5. The procedure of Generating Lu-Dou Dimensions Based on Mathematical Relationships.



the column, and the upper portion is divided into another three segments, each inwardly tapering by 4 *Fen* to form the uniform curve. Based on these design principles, components can be created under specific procedures. As shown in Figure 6, a circular profile of the column is first generated, and it becomes a cylinder after being extruded 3 times. Then for the top 1/3 of the cylinder, the surface inwardly tapering to form the shuttle shape as Juan-Sha.

By applying similar procedures in the program, components in the architecture are generated conveniently through the programming of mathematical calculations and geometric transformations. After that, based on the spatial relationships, the components are assembled together by connecting the datum points, and then a complete parametric model is finally created (Figure 7). Furthermore, if the structure of the architecture exhibits similarities, such as multiple layers or symmetrical layouts, the workload can be further saved by duplicating a similar part and adjusting its size and orientation. Therefore, compared to the conventional modelling method of repeatedly setting dimensions and geometries for each component, parametric modelling greatly enhances the efficiency of the reconstruction process and facilitates adjustments to the model in later stages.

Following the previous procedures, individual components are generated based on mathematical and geometric relationships and stored in a library, from which they can be retrieved and assembled into a whole. Nearly all historical Chinese architecture models can be rapidly generated in accordance with the procedures, only with the exception of some decorative components. To enhance understanding, the generation of columns arrangement and roofs are used as examples to illustrate the overall procedure. Within the Chinese historical architectural

FIGURE 6. Assembly of Components

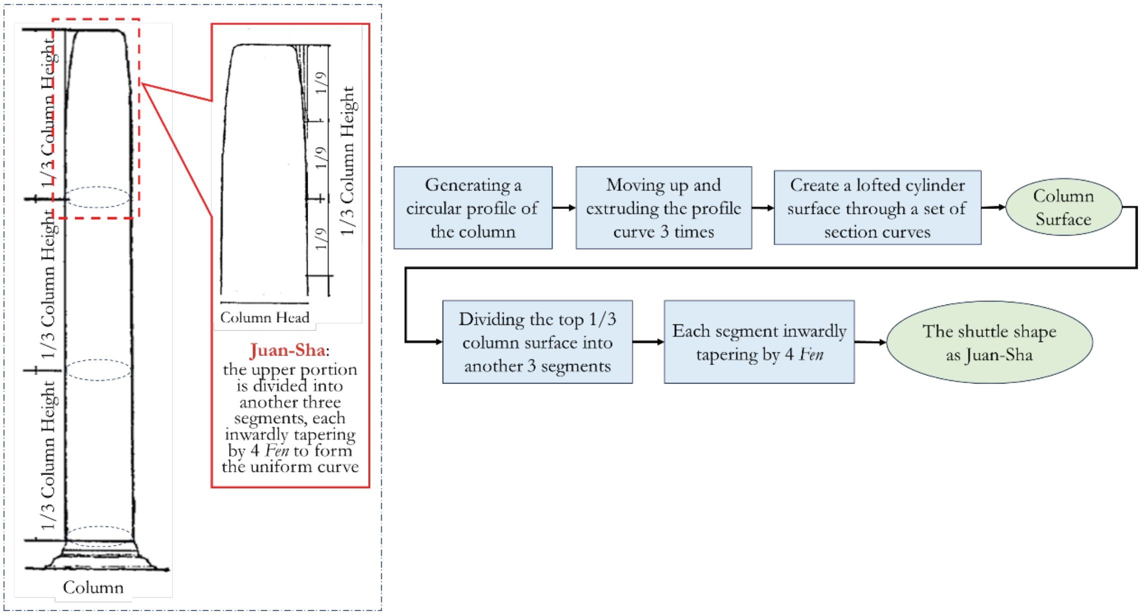
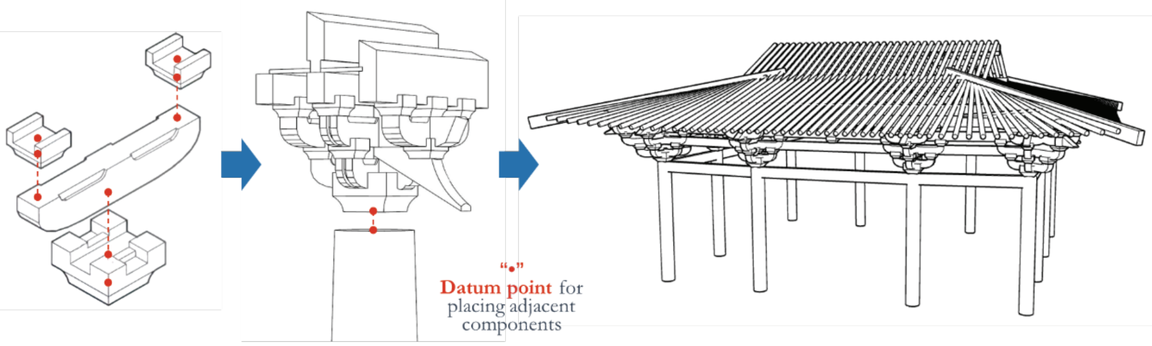


FIGURE 7. Assembly of components.

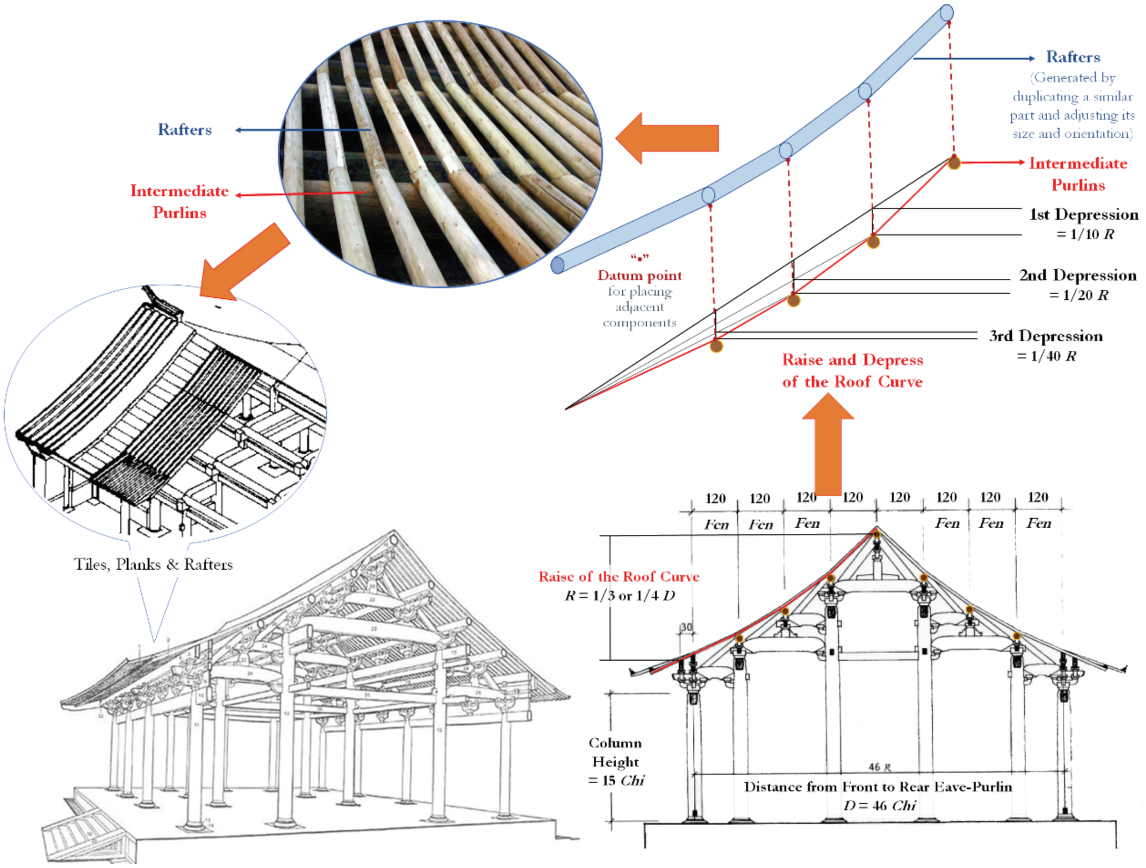


system, apart from the *Cai* and *Fen* in the *Cai-Fen system*, there exist other basic parameters, such as *Chi*. Known as the "Chinese foot," *Chi* is a traditional Chinese unit of length, with one *Chi* during the Song dynasty approximating 31.2cm in modern measurements. Figure 8 depicts the layout of a mansion-type structure house as stipulated in the *Ying-zao Fa-shi*. It can be observed that the structural carpentry, Dou-Gong, and the beams and lintels atop the Dou-Gong are based on the basic units of *Cai* and *Fen*. In contrast, the arrangement of the lower columns, due to their larger scale, employs *Chi* as the basic unit. Moreover, the dimensions of the roof curve are derived from *Chi* as the basic parameter, with the height of the roof (R) typically being $1/3D$ or $1/4D$, where D is the distance from the front to the rear eave-purlin. The geometric shape of the roof curve is strictly regulated in the *Ying-zao Fa-shi*, termed "Ju-Zhe," meaning "raise and depress." Descending from the top, each intermediate purlin drops at a gradient of $1/10R$, $1/20R$, $1/40R$, and so on, to form the curve. After the generation of the columns and roof, other components such as the Dou-Gong between them are retrieved from the library and assembled according to the corresponding sizes, forming the lower layers of the architecture. As shown in the figure 8, the rafters above the roof can also be retrieved from the model library. The size and orientation of each rafter segment are adjusted according to the roof curve, and the datum points are aligned with the datum points of the purlin, completing the assembly. The upper layers of planks and tiles can be retrieved from the library in a similar way, and after duplicating and adjusting, they are finally assembled together to form a complete architecture. It is evident that parametric modelling saves time in modelling repetitive structures, thereby improving efficiency.

Adjustments of the Parametric Model based on Reality

The previous sections have outlined the logic of creating a parametric model from individual components to a whole. When operating the procedures for creating a parametric model of an existing historical architecture, the initial step involves determining the values of the basic parameters *Cai*, *Fen*, and *Chi*. This requires the use of the actual model, which is obtained solely from 3D reconstruction using photogrammetry or laser scanning. Certain dimensions on the surface of the actual model can be measured, such as the distance between columns, the diameter of the column, the length of the Dou-Gong, etc. These measurements, originally in

FIGURE 8. The procedure of Generating Column Arrangement and Roofs Models.



centimetres, are then converted into ancient units, such as *Chi*, through conversion. Following this, the grade of *Cai* used in the architecture can be inferred, and the corresponding values of *Cai* and *Fen* can be determined. Other parameters can then be sequentially derived. In the operation, this step and the previous assembly step are carried out simultaneously. First, reference the visible exterior components on the actual model and place components at corresponding positions. Subsequently, the unseen interior components will be assembled according to the design principles.

Parametric models are first generated strictly according to design principles. However, existing historical architectures may deviate from these standards due to errors in manual construction, as well as subsequent damage and restoration. Therefore, after the parametric model is generated, it is necessary to make adjustments to the sizes and shapes to fit the existing historical building. This can be achieved by adjusting the internal parameters.

Texture Mapping

The parametric model, assembled from individual components and under adjusted, is still a white model, i.e., it lacks surface texture. To reflect the original colour, achieve better display, and reflect the actual conditions of the structure, such as defects, images obtained from UAV photogrammetry are mapped onto the white model through the alignment of the images based on their pose information using the SfM algorithm.

After this process, a final complete model is formed which contains various types of exterior and interior information about the architecture, including the type and size of components, as well as the defects information, and even material information can be assigned.

CASE STUDY: PAN GATE HERITAGE SITE

In the present paper, Pan Gate is selected to investigate the feasibility of the proposed methodology. It is located in Suzhou, China, and is a well-preserved ancient city gate in the country that combines both land and water passages. It holds great significance as a part of the UNESCO World Heritage site, the Grand Canal, and serves as a valuable testament for studying urban construction history and ancient military defence. It currently operates as a scenic area open to tourists.

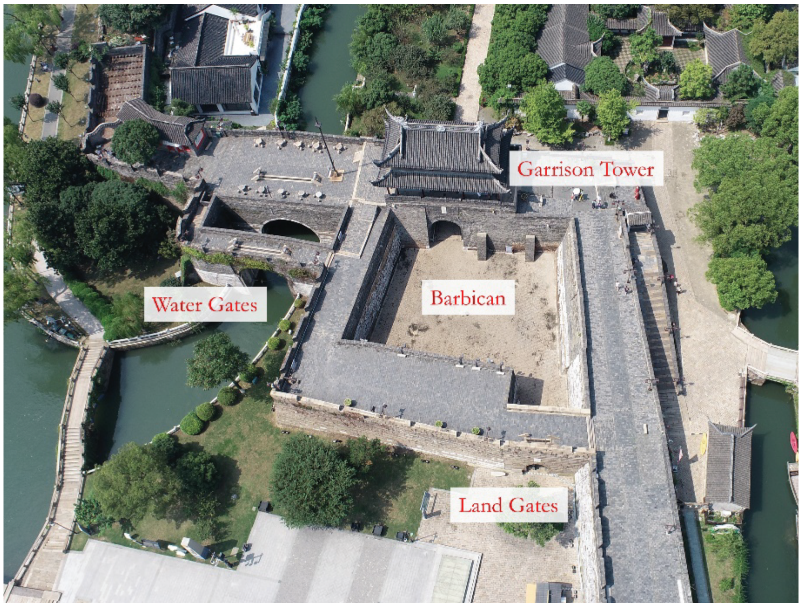
As shown in Figure 9, the site of Pan Gate consists of ramparts with water gates, land gates, and a barbican. The water gates are located on the southern side, while the land gates are on the northern side. A garrison gate tower lies on the interior gate, which is a double eaves hip-and-gable roof mansion. Pan Gate was once restored and rebuilt many times in history. The present structure of the rampart was built in 1351, and was underwent reinforcement, restoration, and reconstruction from 1976 to 1981, resulting in the current appearance. The garrison tower was previously damaged around the 1940s and were rebuilt in 1986. In recent years, efforts have been made to protect the site of Pan Gate, but the recording methods have mostly been manual drawings.

Modelling Pan Gate

Data Acquisition

Based on the layout of Pan Gate, a data acquisition plan was developed. UAV was used to capture the top view of the entire site. It was also used to photograph the surroundings of the

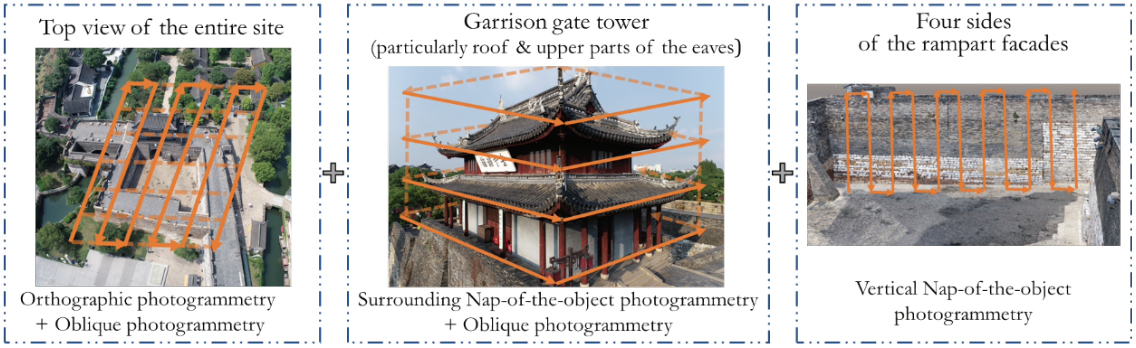
FIGURE 9. Layout of the Pan Gate Historical Site.



garrison gate tower and collect façade images of the barbican walls. Laser scanners were used at the upper and lower sections of the rampart to obtain precise point clouds beneath the eaves of the tower, the interior of the tower, as well as the barbican. Additionally, a separate scan of the barbican wall was conducted for defect inspection. After the data acquisition, the data from different sources were integrated into one spatial coordinate system, based on the positioning information and feature points, as mentioned in the Methodology.

The collection of photogrammetry data was conducted under clear weather condition without harsh sunlight to prevent overexposure. There were also no strong winds when operated the UAV, ensuring stable flight and no blurry image was captured. The shooting period was concentrated within a three-hour window in the morning to avoid inconsistencies in external environment conditions. As shown in Figure 10, various capture orientations were used in different parts of Pan Gate. The top view of the entire site was captured through flight trajectory

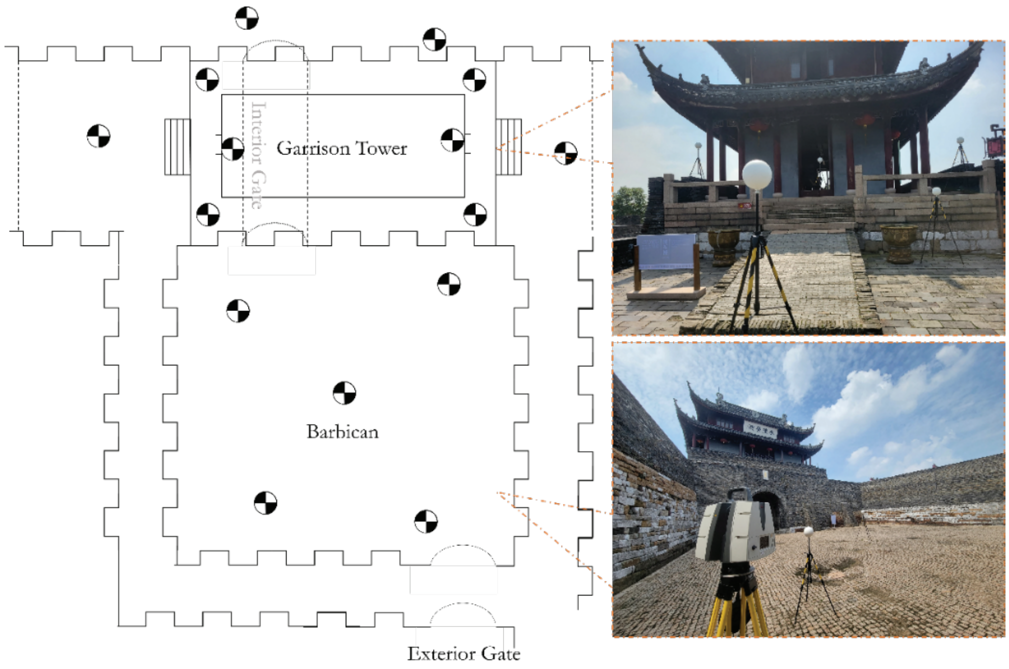
FIGURE 10. Workflow of Image-based Data Acquisition.



planning, which allowed the UAV to automatically capture images from five directions, i.e. each set of images consisted of one orthographic photogrammetry and four oblique photogrammetry taken from different directions with the same tilt angle. The overlap between images was 80%. Nap-of-the-object photogrammetry was conducted manually surrounding the garrison gate tower, particularly focusing on areas such as the roof and upper parts of the eaves that were inaccessible to the laser scanner. Nap-of-the-object photogrammetry was performed on the four sides of the barbican, with each image taken at a distance of 3–5 meters to obtain façade images of the rampart. A total of 1290 photos were obtained. The UAV's built-in RTK (Real Time Kinematic) technology ensured that each photo contained the position of the shooting point, which facilitated the subsequent alignment process.

The laser point cloud data was collected using a Leica ScanStation P40 scanner, which has a scanning range of up to 270 meters and a full field of view of 360 degrees horizontally and 290 degrees vertically. An on-site survey was conducted to plan the setting of the scanning stations and targets, as shown in Figure 11. The scanning stations were positioned on flat ground with good visibility, while the targets were placed in easily identifiable locations with at least three common targets between adjacent stations. On the top of the rampart, 8 scanning stations and 8 sphere targets were arranged to capture the garrison tower especially the places where UAV photogrammetry is inaccessible such as the components under the eaves and the indoor area for data complementing. For the lower ground layer of the rampart, 9 scanning stations were set up, with 7 sphere targets placed. Among them, 5 targets were located inside the barbican, and the other 2 were on the opposite side through the interior gate. The sampling accuracy of the garrison tower and rampart structures was set at 6.3mm@10m. Particularly, for the four sides of the barbican facades, the sampling accuracy was set at 1.6mm@10m for better identification of the defects.

FIGURE 11. Layout of the Sphere Targets.



3D Reconstruction of the Actual Model

After the data acquisition, the images and laser point clouds were processed to generate the actual model which accurately represents the actual architecture in reality. The images of different capture orientations were consolidated and aligned based on coordinate information and feature points. Then a mesh model was generated with textured mapping on it to become a preliminary image-based 3D model. For the laser point cloud data, point clouds were automatically registered based on the constraints of targets after noise reduction. The error of registration was less than 0.005m between each station. Once the image and laser point cloud data were processed separately, they were fused based on coordinate information and feature points to complement the missing part in each model. Due to the higher accuracy of laser scanning, the point clouds served as the foundation. As the laser point clouds of the upper parts which were higher than the eaves were missing, these parts were specifically supplemented using image data. The image data also provided texture information for the model. The actual model representing the appearance of the entire site of Pan Gate was generated after data fusion. However, this actual model only contains the surface information. Therefore, the next step involves parametric modelling to depict the interior structures.

Parametric Modelling of the Parametric Model

Parametric modelling was applied for modelling the garrison gate tower, using Grasshopper, a visual programming plugin in Rhino. As stated in the Methodology, the actual scale of the architecture could be measured in the actual model. Referring to the historical surveying document, the measurement units *Chi* of the Song Dynasty was used as a reference scale to determine the grade of *Cai* used in the garrison tower, consequently, the value of *Fen* was obtained as the basic parameter. Thus, the dimensions of the garrison tower components could be derived through mathematical relationships. Combining with the geometric relationships outlined in design principles, components such as columns, beams, Dou-Gong (bracket sets), lintels, roof tiles, steps, and eaves were generated. For example, as shown in Figure 12 and 13, the Lu-Dou

FIGURE 12. Grasshopper Program for Generating Lu-Dou.

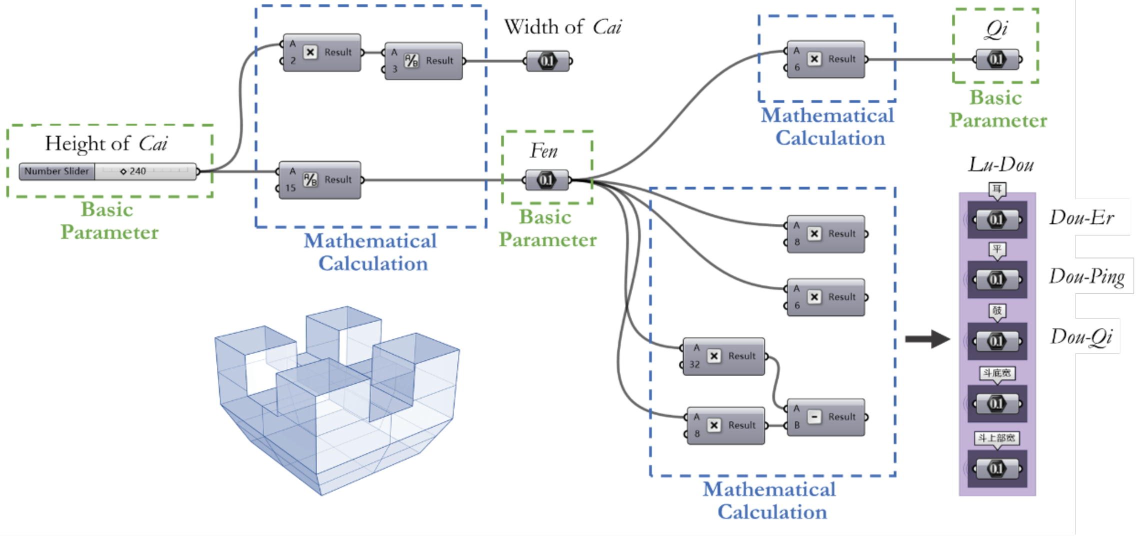
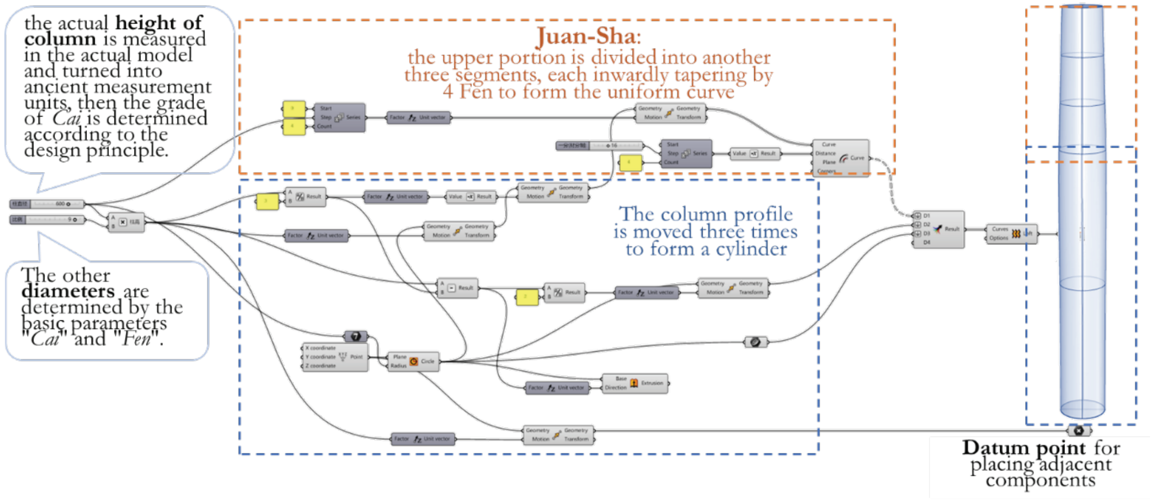


FIGURE 13. Grasshopper Program for Generating the Column with Juan-Sha.



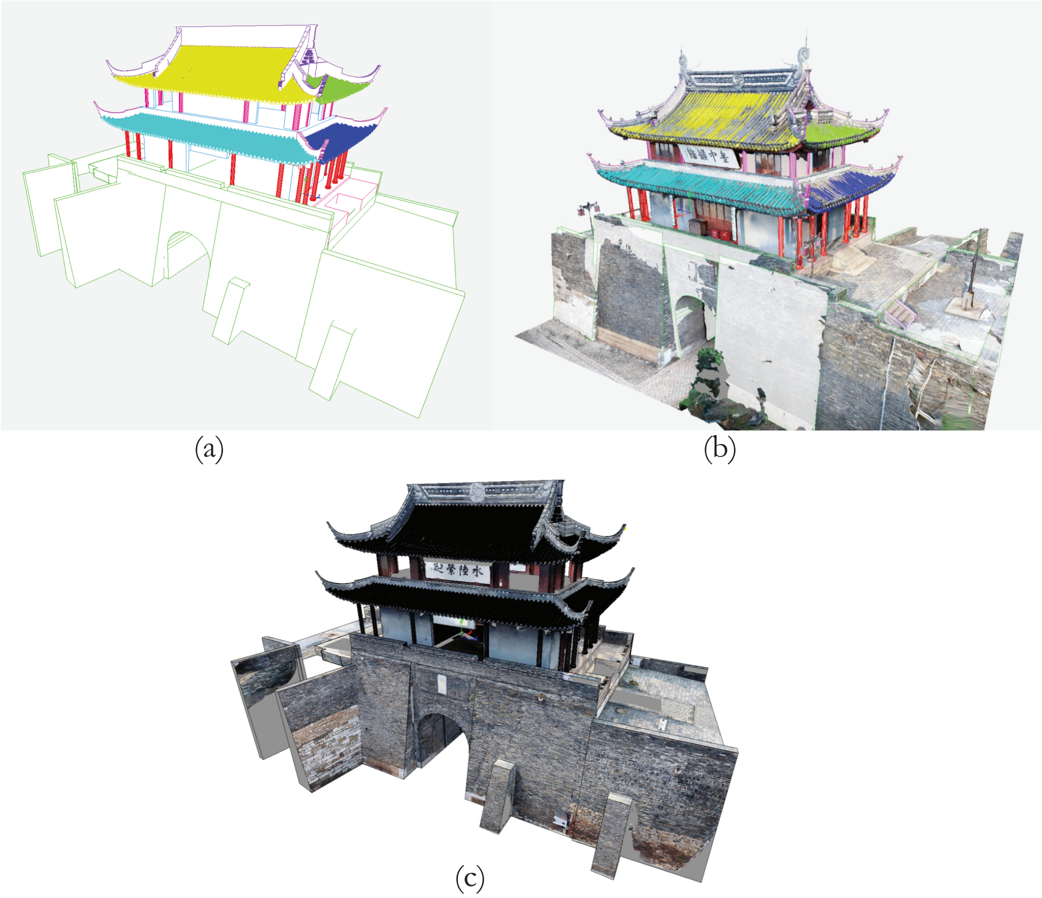
and Column, which are sub-components of the column bracket set (Figure 4), were generated in Grasshopper based on the procedures in Methodology. By measuring the realistic size of the column set in the actual model and converting the unit to the ancient unit *Chi* in the Song Dynasty, the closest grade of *Cai* could be found, as well as the *Fen*. Then the other relevant dimensions such as Dou-Er, Dou-Ping, Dou-Qi and the column diameter could be generated automatically. Meanwhile, the geometry of the components was created according to the geometric relationships, such as Juan-Sha of the column.

As the steps outlined in the Methodology, based on the positions of the exterior components observed in the actual model, corresponding parametric components were placed accordingly. By adhering to the positional relationships outlined in the design principles, the exterior and interior components were assembled by connecting the datum points to create a comprehensive parametric model (Figure 14(a)), where different components are visually differentiated using distinct colours. Repetitive components like columns were efficiently generated using operations such as copying, moving, and mirroring, saving time during the modelling process. Decorations on the garrison tower, such as stone carvings, were not included because they were not parametric elements. As stated in the Methodology, since there were deviations between the conceptual design principles and the actual construction process, the positions and sizes of the parametric components were fine-tuned to fit the actual model, ensuring they accurately reflect the actual architecture in reality, as depicted in Figure 14(b). Textures were finally mapped onto the parametric model to enhance its visual presentation and enrich the defect information (Figure 14(c)).

Evaluation of the Accuracy of the Parametric Model

The accuracy of the parametric model was evaluated by comparing it to the actual model. The parametric model was constructed based on the shape and dimensions of the actual model. Therefore, the actual model was set as a reference in the comparison. Since the parametric model includes both the exterior and interior components, while the actual model only represents the surface of the architecture, the comparison focused solely on their surface parts. The

FIGURE 14. (a)the parametric model with different component colours; (b) the fit between the parametric model and the actual model; (c) the parametric model with texture.



(a)

(b)

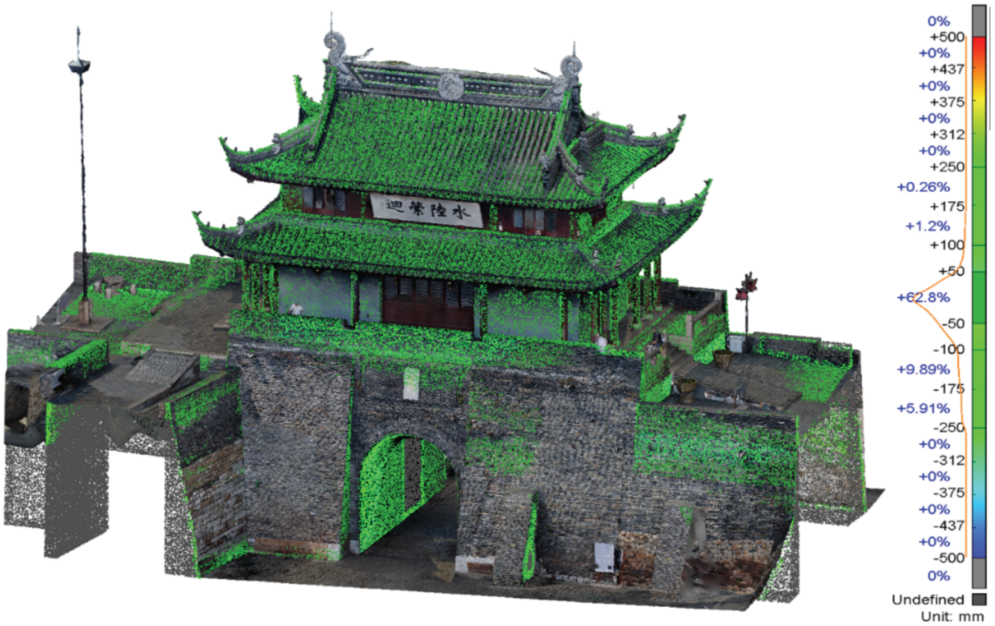
(c)

point clouds of the parametric model's surface were obtained through sampling and aligned with the actual model in the same coordinate system to assess the differences. As shown in Figure 15, the analysis was conducted in Cyclone 3DR, where the distances between the point clouds of the parametric model and the surface of actual model were calculated. The result indicated that more than 50% of the points exhibited deviations within 50mm, and all points exhibited deviations within 250mm, meeting the third level accuracy requirements specified in the Chinese standard of historical architecture surveying (CHT6005-2018). Considering that special decorations (such as stone carvings) and interference elements (such as streetlights, furniture, and vegetation) were included in the actual model, which were not incorporated in the parametric model, the analysis demonstrated that the parametric model well reflected the actual architecture and can be used for further applications on H-BIM platforms, such as structural analysis, defect inspection, etc.

Management on the H-BIM platform

Due to the information compatibility between software like Rhino and Revit, parametric models generated by Grasshopper, including their semantic information, allow for smooth interoperability with BIM platforms. This benefits the subsequent management of historical architectures

FIGURE 15. Deviation Between the Parametric Model and the Actual Model.



by relevant personnel. In this study, the parametric model of Pan Gate will be loaded onto a WEBGL-based BIM platform 3DVaaS to provide applications for the relevant personnel. This will help them efficiently obtain relevant information during the preservation, restoration, and promotion processes, reducing time and monetary costs, and making the management process more sustainable. Following are some feasible applications.

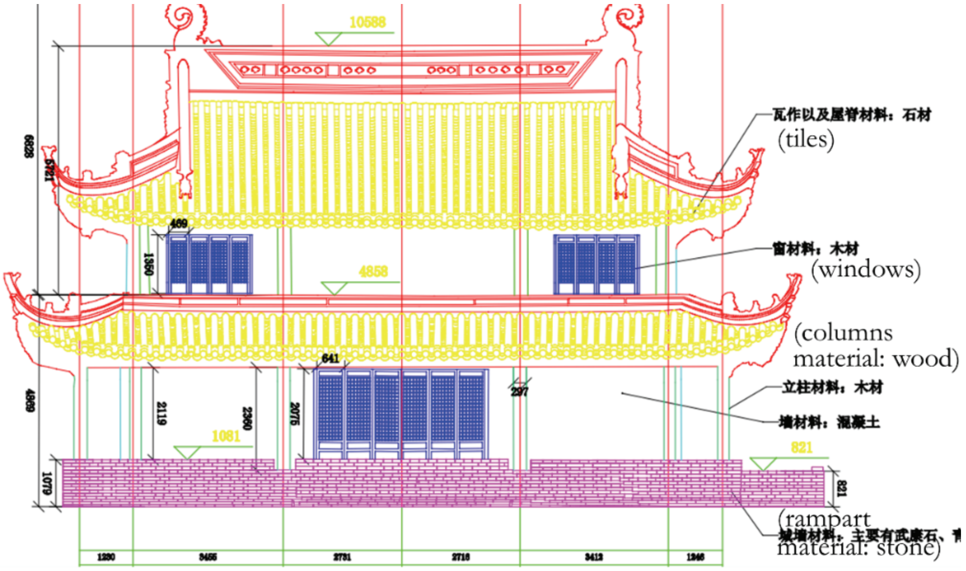
Structural Analysis

During the study of historical architecture, archaeologists and architects often require access to interior structural information to comprehend the design concepts, popular techniques, and craftsmanship of that construction period. The parametric model presents information on both the interior and exterior components, enabling the generation of plans, elevations, or section graphs on any desired plane. Simultaneously, dimensions can be calculated based on parameter information. If material information was previously entered into the individual component families, it can also be displayed. Afterwards, only decorative non-parametric components need to be drawn to generate complete drawings, which is more convenient than traditional drawings. Figure 16(a) showcases the elevations of the Pan Gate generated from the parametric model. The parametric model also has capabilities in assessing structure and foundation stability.

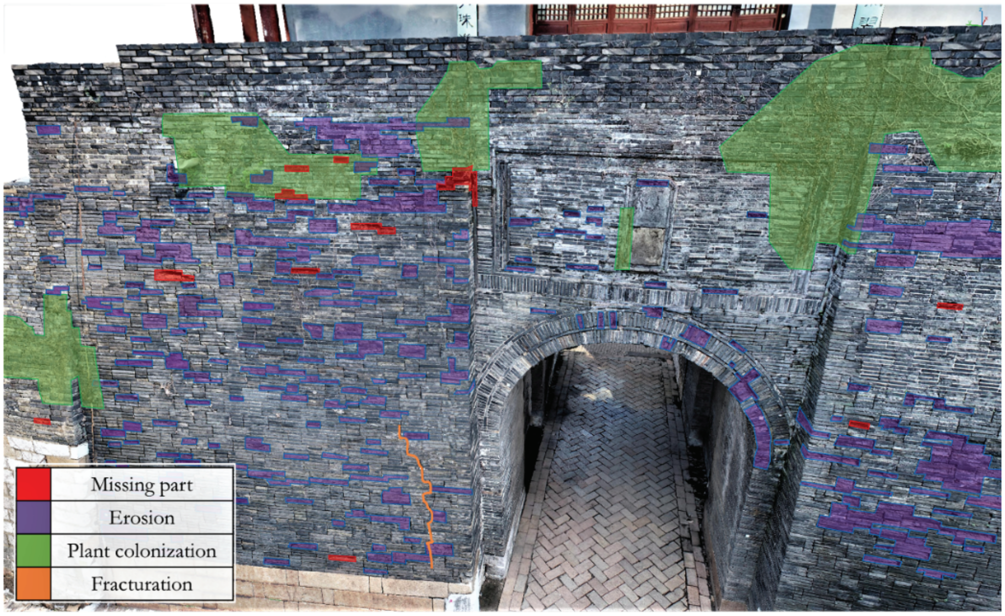
Defect Inspection

Ancient walls hold significant historical value and require preservation. The walls of Pan Gate, having undergone multiple damages and repairs, exhibit various types of defects, such as missing bricks, weathering erosion, plant colonisation and fractures, which need to be monitored regularly. In this case study, high-resolution images captured by UAV photogrammetry are used as texture mapping on the surface of the parametric model of Pan Gate to reproduce the original appearance of the architecture. Various defects have been identified and annotated in the

FIGURE 16. Management of Pan Gate on the H-BIM platform.



(a) Structural Analyse



H-BIM platform, each type of defect is assigned a specific family, as shown in Figure 16(b). This digital management facilitates relevant personnel in accurately locating the defects and quickly accessing related information, thereby enabling comprehensive planning for restoration schemes.

DISCUSSION

In the case study, UAV photogrammetry was used to capture the top view of the entire site, the surroundings of the garrison gate tower and the facades of the barbican. Laser scanning was used at the upper and lower sections of the rampart to obtain precise point clouds of beneath the eaves of the tower, the interior of the tower, as well as the barbican. The two sources of data were integrated to supplement each other. Parametric components such as columns, beams, Dou-Gong (bracket sets), lintels, roof tiles, steps, and eaves were generated through programming languages and then assembled to create a complete model, which saves the workload compared to the conventional modelling method. The parametric model met the accuracy requirement and well reflected the existing architecture. Several applications of the model such as structural analysis and defect inspection show that the parametric H-BIM brings benefits to the relevant personnel in the protection, restoration and dissemination process, and promotes sustainable management for the historical architectures.

The proposed method for generating the parametric model offers the following advantages.

1. Inclusion of both exterior and interior information: Unlike conventional "3D reconstruction-only" models or NURBS models, which only contain the appearance of the architectures, the parametric model includes component information from the exterior to the interior. In addition, each component's type, size, and even material information is assigned within it.
2. Integration of multisource information: The data collected in the early stage is integrated into the parametric model. High-resolution images are mapped onto the model as texture, allowing the parametric model to reflect the original appearance and the defect information in reality.
3. Lightweight model: Compared to 3D reconstruction mesh models which consist of a large number of faces, the parametric model obtained by the proposed method significantly reduces the number of mesh faces while accurately fitting the real architecture. This makes the model run more smoothly on BIM platforms.

CONCLUSION

This study focuses on overcoming the challenges in the modelling process of Chinese historical architectures. Photogrammetry images and laser scanning point clouds are fused to avoid missing data. Parametric modelling based on ancient design principles is introduced to efficiently generate those components with unique and complex geometry and then obtain a model which comprehensively contains both exterior and interior information of the architecture. The created model is fine-tuned and textures are mapped on it to reflect the actual existing architecture. A current limitation is that at present the parameter library only contains components of the structural carpentry in the Song Dynasty. In the subsequent works, more component types and styles from different dynasties should be supplemented to expand the representation of historical architecture. Future research will focus on further enhancing the automation level of parametric modelling. The parametric elements will be formed into a dataset for training deep learning algorithms to recognise the types, sizes, positions, and other information of components from the collected data, thus automatically generating a complete parametric model.

Acknowledgement

This research is supported by the 2022 Suzhou Science and Technology Programme, 2022SS51, and the Design School Intelligent Built Environment, Xi'an Jiaotong-Liverpool University.

REFERENCES

Abd ElWahab, H. A., Bakr, A. F., & Raslan, R. A. (2019). Towards a parametric plug-in for conservation of built heritage. *Alexandria Engineering Journal, 58*(1), 325–331.

Aicardi, I., Dabove, P., Lingua, A. M., & Piras, M. (2016). Integration between TLS and UAV photogrammetry techniques for forestry applications. *Iforest-Biogeosciences and Forestry, 10*(1), 41.

Balado, J., Frías, E., González-Collazo, S. M., & Díaz-Vilariño, L. (2022). New trends in laser scanning for cultural heritage. In *New Technologies in Building and Construction: Towards Sustainable Development* (pp. 167–186). Singapore: Springer Nature Singapore.

Barazzetti, L. (2016). Parametric as-built model generation of complex shapes from point clouds. *Advanced Engineering Informatics, 30*(3), 298–311.

Böttger, H. M., Arce Bazán, C. J., & Saarman, N. P. (2016). 3D laser scanning for preservation and structural monitoring of historic California adobe missions. *Journal of Green Building, 11*(4), 1–14.

Chandel, A., Yadav, S. K. S., Agarwal, A. K., Shukla, S., & Poddar, J. (2022). 3D Reconstruction of Heritage Site Using Terrestrial LiDAR Scanner (Tls): A Case Study of a Section of Gulistan-E-Iram, Lucknow. *Sustainable Infrastructure Development*, 79–89.

Chevrier, C., Charbonneau, N., Grussenmeyer, P., & Perrin, J. P. (2010). Parametric documenting of built heritage: 3D virtual reconstruction of architectural details. *International Journal of Architectural Computing, 8*(2), 135–150.

Chiabrando, F., Donato, V., Lo Turco, M., & Santagati, C. (2018). Cultural heritage documentation, analysis and management using building information modelling: state of the art and perspectives. mechatronics for cultural heritage and civil engineering, 181–202.

Costantino, D., Pepe, M., & Restuccia, A. G. (2023). Scan-to-HBIM for conservation and preservation of Cultural Heritage building: The case study of San Nicola in Montedoro church (Italy). *Applied Geomatics, 15*(3), 607–621.

Dore, C., & Murphy, M. (2013, October). Semi-automatic techniques for as-built BIM façade modeling of historic buildings. In *2013 Digital Heritage International Congress* (DigitalHeritage) (Vol. 1, pp. 473–480). IEEE.

Dylla, K., Frischer, B., Müller, P., Ulmer, A., & Haegler, S. (2010). Rome reborn 2.0: A case study of virtual city reconstruction using procedural modeling techniques.

Gomes, L., Bellon, O. R. P., & Silva, L. (2014). 3D reconstruction methods for digital preservation of cultural heritage: A survey. *Pattern Recognition Letters, 50*, 3–14.

Gursel, I., Sariyildiz, S., Akin, Ö., & Stouffs, R. (2009). Modeling and visualisation of lifecycle building performance assessment. *Advanced Engineering Informatics, 23*(4), 396–417.

Haegler, S., Wonka, P., Arisona, S. M., Van Gool, L., & Müller, P. (2010, June). Grammar-based encoding of facades. In *Computer Graphics Forum* (Vol. 29, No. 4, pp. 1479–1487). Oxford, UK: Blackwell Publishing Ltd.

Hu, Z., & Qin, X. (2021). Extended interactive and procedural modeling method for ancient Chinese architecture. *Multimedia Tools and Applications, 80*, 5773–5807.

Huang, H., Zhang, C. & Hammad, A. (2021). Effective scanning range estimation for using TLS in construction projects. *Journal of Construction Engineering and Management, 147*, 04021106.

Huo, P., Hou, M., Dong, Y., Li, A., Ji, Y., & Li, S. (2020). A method for 3d reconstruction of the Ming and Qing official-style roof using a decorative components template library. *ISPRS International Journal of Geo-Information, 9*(10), 570.

Li, Jie. (1100). Ying-zao Fa-shi. Kaifeng: Song Dynasty Government. In Chinese.

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2017). Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction, 84*, 195–206.

Liang, Sicheng. (1983). Annotated Yingzao Fashi. Beijing: China Architecture & Building Press. In Chinese.

Liu, J. (2018). Component-driven pocedural modeling for ancient Chinese architecture of the Qing Dynasty. *International Journal of Architectural Heritage, 12*(2), 280–307.

Liu, H., & Wu, C. (2019). Developing a scene-based triangulated irregular network (TIN) technique for individual tree crown reconstruction with LiDAR data. *Forests, 11*(1), 28.

Liu, H., Xie, L., Shi, L., Hou, M., Li, A., & Hu, Y. (2019). A method of automatic extraction of parameters of multi-LoD BIM models for typical components in wooden architectural-heritage structures. *Advanced Engineering Informatics, 42*, 101002.

Massafra, A., Prati, D., Predari, G., & Gulli, R. (2020). Wooden truss analysis, preservation strategies, and digital documentation through parametric 3D modeling and HBIM workflow. *Sustainability, 12*(12), 4975.

Microsoft, Iconem, Greek Ministry of Culture and Sports. (2021). Ancient Olympia: Common Grounds.

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey, 27*(4), 311–327.

Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing, 76*, 89–102.

Penttilä, H., Rajala, M., & Freese, S. (2007). Building information modelling of modern historic buildings. Predicting the Future, 25th eCAADe Konferansı, Frankfurt am Main, Germany, 607–613.

Pesci, A., Casula, G., & Boschi, E. (2011). Laser scanning the Garisenda and Asinelli towers in Bologna (Italy): Detailed deformation patterns of two ancient leaning buildings. *Journal of Cultural Heritage, 12*(2), 117–127.

Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., & Grau-Bové, J. (2018). BIM for heritage science: a review. *Heritage Science, 6*(1), 1–15.

Qing Ministry of Works. (1734). Gong-cheng zuo-fa ze-li (Qing dynasty Architecture Method). Beijing: Qing Dynasty Government. In Chinese.

Radanovic, M., Khoshelham, K., & Fraser, C. (2020). Geometric accuracy and semantic richness in heritage BIM: A review. *Digital Applications in Archaeology and Cultural Heritage, 19*, e00166.

Santos, D., Sousa, H. S., Cabaleiro, M., & Branco, J. M. (2023). HBIM application in historic timber structures: a systematic review. *International Journal of Architectural Heritage, 17*(8), 1331–1347.

Shen, Y., Zhang, E., Feng, Y., Liu, S., & Wang, J. (2021). Parameterising the curvilinear roofs of traditional chinese architecture. *Nexus Network Journal, 23*, 475–492.

Simeone, D., Cursi, S., & Acierno, M. (2019). BIM semantic-enrichment for built heritage representation. *Automation in Construction, 97*, 122–137.

Soleymani, A., Jahangir, H., & Nehdi, M. L. (2023). Damage detection and monitoring in heritage masonry structures: Systematic review. *Construction and Building Materials, 397*, 132402.

State Bureau of Surveying and Mapping. Specification for ancient building surveying and mapping (CH/T 6005-2018). In Chinese.

Suermann, P. C., & Issa, R. R. (2009). Evaluating industry perceptions of building information modelling (BIM) impact on construction. *Journal of Information Technology in Construction (ITcon), 14*(37), 574–594.

Surový, P., Yoshimoto, A., & Panagiotidis, D. (2016). Accuracy of reconstruction of the tree stem surface using terrestrial close-range photogrammetry. *Remote Sensing, 8*(2), 123.

Sutherland, I. E. (1968, December). A head-mounted three dimensional display. In *Proceedings of the December 9–11, 1968, fall joint computer conference, part I* (pp. 757–764).

Tomaževič, M., & Lutman, M. (2007). Heritage masonry buildings in urban settlements and the requirements of Eurocodes: Experience of Slovenia. *International Journal of Architectural Heritage, 1*(1), 108–130.

Vlahakis, V., Karigiannis, J., Tsotros, M., Gounaris, M., Almeida, L., Stricker, D., … & Ioannidis, N. (2001). Archeoguide: first results of an augmented reality, mobile computing system in cultural heritage sites. *Virtual Reality, Archeology, and Cultural Heritage, 9*(10.1145), 584993–585015.

Yao Chengzu, Zhang Zhigang, Liu Dunzhen. (1982). Ying-Zao Fa-Yuan, China Architecture & Building Press. In Chinese.