Prospect of architectonic grammar reconstruction from dense 3D point clouds: Historical building information modeling (HBIM) of Guangdong cultural heritages

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Abstract:

Building information modeling (BIM) of cultural heritages, i.e., historic building information modeling (HBIM), advances the monitoring, maintenance, restoration, and virtual exhibitions of historical buildings. However, due to the elaborate styles and the unavoidable erosion and renovation, the reconstruction of HBIM from the prevalent raw data, such as point clouds and images, is very challenging, especially parametrical and semantic modeling. Recent studies have noticed the potential of architectonic grammar for facilitating parametric and semantic reconstruction. In this paper, we investigate the manual modeling of cultural heritage with the architectonic grammar and propose a roadmap consisting of four levels of automation, i.e., 'calibration,' 'selection,' 'combination,' and 'generation,' of the architectonic grammar reconstruction. Further quality improvement and cost analysis of these four levels show that 'calibration' and 'selection' are the most suitable options currently for real-world applications. This study inspires the future application of architectonic grammar to facilitate the parametric and semantic HBIM reconstruction and explores the prospect of a new HBIM reconstruction schema.

Keywords:

HBIM, BIM automation, cultural heritage, architectonic grammar, parametric modeling, building semantics, automated model reconstruction

1 Introduction to architectonic grammar reconstruction

Building information modeling (BIM) is a digital representation of physical and functional characteristics of a facility to enhance data interoperability and serves as the fundamental information infrastructure to facilitate data sharing, construction control, facility management, and decision making (NIBS 2015). When applied in cultural heritage, i.e., historic buildings, BIM is known as historic BIM (HBIM) (Murphy et al. 2009). HBIM has received much attention in the past decade due to its promising applications in heritage monitoring, maintenance, restoration, and virtual exhibitions (López et al. 2018).

However, HBIM is not as prevalent as its counterpart of modern buildings, and its automation supported by the software is still limited (López et al. 2018). The reconstruction of HBIMs could be much more challenging than that of BIMs. Because unlike modern buildings which are prone to be highly regular, concise, or compact, historic buildings are always highly elaborate, both in structures, e.g., the wooden composition of Shanxi Hanging

Temple, and decorations, e.g., the facades of Cathédrale Notre-Dame de Paris (Pocobelli et al. 2018). Therefore, the complexity of geometry, semantics, and topology of heritages could be very high. Furthermore, erosion and refurbishment are unavoidable in cultural heritages during their long history, which improves the complexity of HBIM reconstruction.

Existing approaches to HBIM take advantage of 3D scanning and photography to capture cultural heritages' surface information (Murphy et al. 2009; Quattrini et al. 2015). Once captured, mesh models can be created by triangulation from point clouds or performing structure-from-motion (SfM) algorithms on images, which is mature and automatic. Next, to create semantic and parametric HBIMs, interactive and automatic solutions have been investigated. For example, Murphy et al. (2009) introduced an HBIM system to map the BIM objects from a parametric object library onto point clouds. However, the conversion from point clouds or mesh models to parametric components of these HBIM systems still requires much manual effort. Moreover, BIM semantics recognition by segmentation is a typical schema of automatic reconstruction, which could be further categorized into (i) heuristic and (ii) learning approaches (Bassier et al. 2019; Chen et al. 2019). However, segmentation with heuristic rules is limited to simple geometry shapes (Musialski et al. 2013). Moreover, segmentation by learning relies on burdensome manual annotations for training. Furthermore, both paradigms of segmentation are sensitive to data imperfections, e.g., occlusion and clutter in point clouds or mesh models.

Recently, architectonic grammar is exploited for the parametric reconstruction of buildings as a segmentation-free approach. The architectonic grammar regularizes the expressions of elements, forms, and styles from the ground plan to the rooftop (Cole 2002) and is presented in our built environments from the main structure to the smallest details. It has some essential properties that facilitate parametric and semantic reconstruction of HBIM. First, architectonic grammar is highly extensible to different architectural styles based on the concept of meta-grammar. Traditional grammars could be found out in the cultural heritages; meanwhile, some architectural modernists, such as *Frank Gehry* and *Zaha Hadid*, have deviated their distinguishable ones. Secondly, architectonic grammar holds a hierarchy from the main structures to the smallest details. More specifically, the grammar covers the definitions of (i) parameters, (ii) geometric primitives, (iii) components, and (4) component relations. Consequently, researchers and engineers can configure the most suitable hierarchy level for HBIM reconstruction. For example, the HBIM system can automatically adjust the parameters or select appropriate geometric primitives and parameters of the semantic components. Thirdly, the architectonic grammar is compatible with some statistical reasoning frameworks (Kalogerakis et al. 2012), advancing the automatic semantics recognition while preserving the interpretation compared with some "black-box" segmentation-based reconstruction.

This paper aims at proposing a roadmap for the future automation of the architectonic grammar reconstruction from point clouds. First, we select a set of Guangdong cultural heritage sites and collected dense and colorful 3D point clouds. A manual process then reflects how the architectonic grammars of the target heritage buildings can be organized into the Grasshopper diagrams. A roadmap consisting of four levels of automation is presented in contrast with the manual modeling results. We recommend the 'calibration' and the 'selection' levels for practitioners.

2 The case of Guangdong cultural heritage

A pilot study was conducted on a case in Sanxiang Town, Zhongshan City, Guangdong Province, China, as shown in Figure 1. We focused on three cultural heritage sites' colorful point clouds scanned by a drone. The LiDAR point cloud includes one Tower named Wenge and three watchtowers (486 MB compressed on disk), which were relatively complete and uniformly sampled in the LASzip Compressed Lidar (.laz) format. The data set's coordinate system was WGS 84/UTM zone 49N (EPSG: 32649).

Figure 1. Three study sites as circled around the Old Street, Sanxiang Town, Guangdong

Wenge Pagoda, located in the Xuzai community of Sanxiang Town, was built in 1747 in Qing Dynasty, which has a 273-year-long history as for now. The tower has five stories and is 30 meters high, covering an area of 39 square meters, which was rebuilt three times in 1819, 1895, as well as 1984 and announced as a cultural relic protection unit in Zhongshan City in 1990. A dense cloud of 29,606,820 colorful points were collected from the photogrammetric model of drone photographs. The mean volume density of it is 7272552.5 pts/m^3.

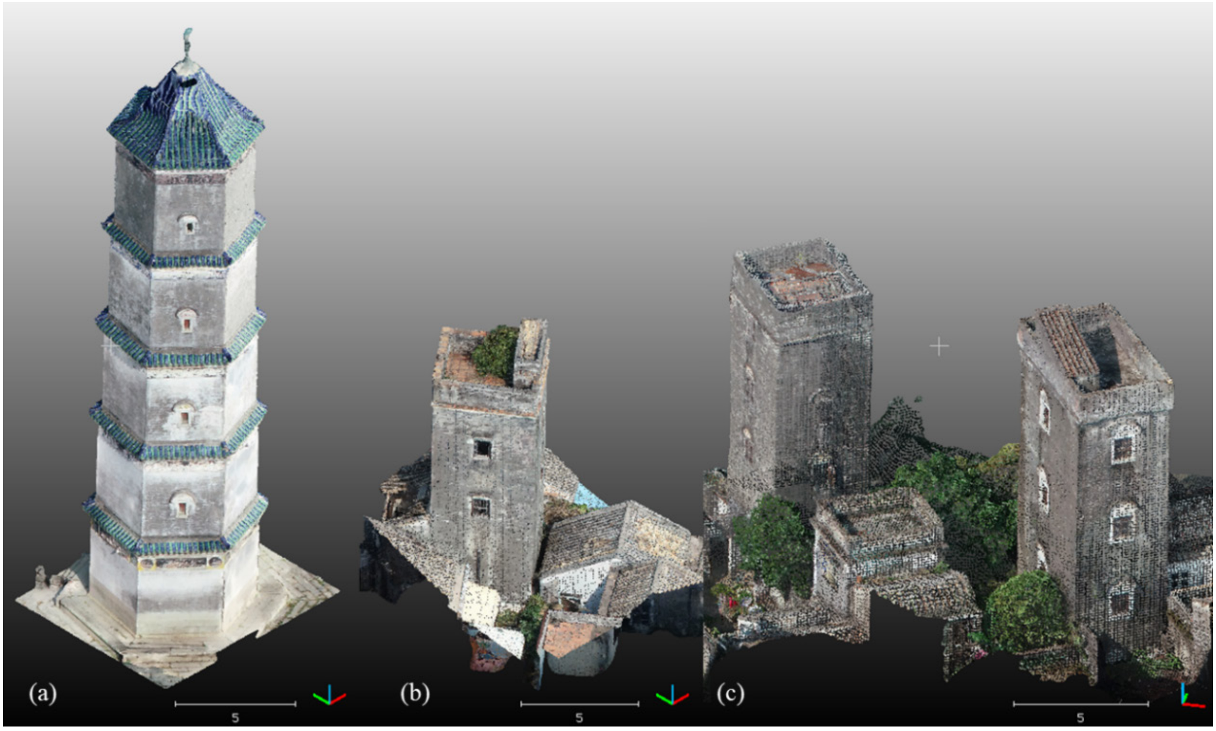

Figure 2. Dense point clouds of cultural heritage buildings, with a density of >10,000 pts/m². (a) Wenge Pagoda (29,606,820 points), (b) a watchtower (13,571,861 points), (c) twin watchtowers (20,853,279 points)

Watchtowers as a typical historic site in Sanxiang Town are scattered in the old streets and alleys, especially in Baishi Village. They were built from the end of the Qing Dynasty to the Republic of China for military use. These watchtowers have been listed in the category of Historical Buildings in Zhongshan City in 2009 and listed in the Historical and Cultural Protection Areas of Sanxiang Town. Three watchtowers of them were scanned and collected in the point cloud datasets. The first set with one tower has 13,571,861 colorful points while the second set including two watchtowers of 20,853,279 colorful points. The point densities in the datasets are over 10,000 pts/m^2.

3 Baseline parametric modeling

We utilized the Grasshopper, a built-in modeling language and plug-in on the Rhino platform (ver. 6), for the manual parametric modeling. Grasshopper is a non-uniform rational basis spline (NURBS) based on visual programming language and 3D modeling software. The value of Grasshopper lies in parametric modeling and human-machine interactive design. Besides, Rhino can create, edit, analyze, and transform NURBS curves, surfaces, and entities in the aspect of complexity, angle, or size—though Rhino 6 needs relatively high computer configuration. The laptop for the experiment runs a Windows 10 (64 bits) on Intel i9-9980HK CPU, 16GB memory, and NVDIA Quadro T2000 GPU.

First, the dense point clouds were converted from the data set to ASTEM E57 (.e57) format and Wavefront object (.obj) for Rhino's use. The three sets of point clouds were centered on the origins. Grasshopper was utilized to rebuild the reference points from the point cloud data. In sequence, it is used to be the center point of the reference plane in the model. Then, the shape's contour line or curve battery by setting the plane figure's relative length details and shows different its location through translation or rotation. Then, the contour line or curve battery of the shape may move up or down, expand or shrink through number battery to form other flat figures of different heights or sizes needed. After that, the shape surfaces can form from external contour lines or curves through covering surfaces. The operator might also blast curves and then extract, and loft surfaces separately if some surfaces are not needed ultimately. Eventually, a series of planes from every module is made up of generated planes in the module and then are composed of the whole model surface.

The architectonic grammar diagram of the pagoda in Grasshopper, as shown in Figures 3a and 3b, consists of six modules. The base and the first layer of the pagoda presents in the first module. Firstly, the reference anchor point (0,0,0) needs to be found from the 3D could point model. Secondly, the base's hexagonal contour line of with 5 meters on each side is generated with the reference point as the center point of the graph, then it rotates 15 degrees counterclockwise and moves up 0.4 meters. Then, the hexagonal contour line of the base goes to move up 0.4 meters and do the same generation and rotation again. In sequence, the first layers' hexagonal contour line is produced by moving up or down 0.35 meters while expanding to 1.1 times or shrinking 0.95 times. Lastly, the above generated hexagonal contour lines are combined into a line composition and then the set of lines lofting into the first layer plane together with the base one. From the first layer to the second one, the top hexagonal contour line of the first layer is lifted 4.5 meters to become the middle one of the first layer. Next, the same steps are continued. Then, the generation from the first to the second is applicable to the third, fourth, and fifth layers. In the tower top module, the spire performs by lifting the fifth layer's reference anchor point by 3.6 meters. The six points of the middle hexagonal contour line of the fifth layer move up 0.6 meters and then shrinks to 0.8 times to be the reference points for the tower roof design. In the end, the spire's point is duplicated to generate the circular reference line, and then the six planes are set out to get the top roof of the tower.

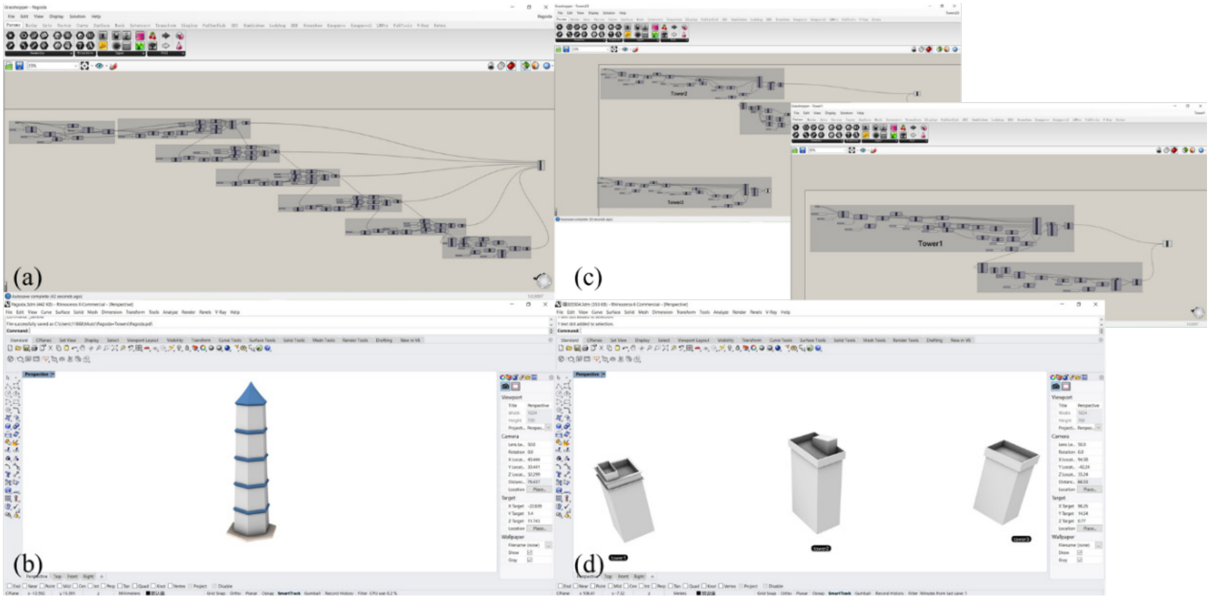

Figure 3. Grasshopper diagram and parametric models. (a) Diagram for Wenge Pagoda, (b) 3D view of (a), (c) diagrams for the watchtowers, (d) 3D view of (c)

The architectonic grammar diagram of the first tower in Grasshopper, as shown in Figure 3c and 3d, consists of 2 modules. The body layer of the tower presents in the first module. Firstly, the reference anchor point (0, 0, 0) needs to be found from the 3D could point model. Next, the base’s rectangular contour line is generated with the reference point as the center point of the graph, and then it rotates 35 degrees counterclockwise and moves up 8 meters to generate the rectangular contour line of the lower top layer. Next, the top layer’s rectangular contour lines are produced by moving up 0.1 meters, up 0.1 meters, or down 0.895 meters while expanding to 1.1 times or shrinking 0.95 times. Lastly, the rectangles cover, and lines are lofting into planes. Therefore, the surface composition of the tower’s body layer performs in the model. In the second module, the floor of the roof covers through the principle called the three points to form a plane. Next, the floor of the affiliated small house generates by the above reference point and setting the length of X and Y. Finally, a set of horizontal rectangular contour lines of the house are produced through moving up 1.8 meters or 0.895 meters meanwhile shrinking 0.9 times. Eventually, a series of rectangles cover and lines lofting into planes. Similarly, in the last Grasshopper diagram, the second tower’s modeling process is divided into two modules, and the third towers are divided by 1 module. The sequence of the first tower’s modeling is also adaptive to these two.

These restoration models of ancient buildings in Guangdong through computational design software preliminarily perform the buildings' main body shape. Therefore, what is fundamental and essential in reserving while reconstructing the cultural heritage field is that the broken and incomplete physical architectural model shows again in public in the form of virtual architectural models through novel digital tools. Furthermore, one of the usual computational design methods is parametric design, a design process in which the engineering itself is programmed as a function and a process. The design process is automatically realized by modifying the initial conditions and obtaining the engineering results by computer calculation.

4 A roadmap to the automation

The automation of architectonic grammar reconstruction can be projected and classified into four levels, as shown in Figure 4. We noticed that the diagrams in Grasshopper were comprised of four types of grammar components, i.e., (i) parameters, (ii) geometric primitives, (iii) components, and (iv) relations to new components. Therefore, the most straightforward automation is to let the machine fine-tune the parameters, while the whole diagram structure designed manually remains unchanged. The most challenging automation level is automatic incremental design or revision of new components, while no apparent work demand is there for human modelers. Note that the automation roadmap and the levels are independent of the Grasshopper + Rhino and compatible with other parametric design tools such as Dynamo + Revit.

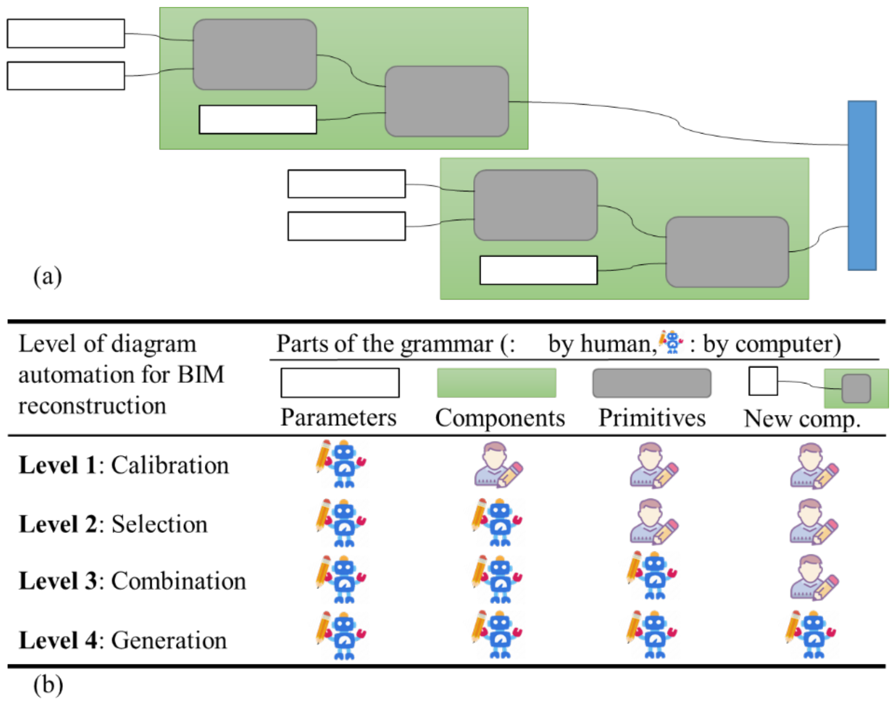

Figure 4. Four levels of prospect of automation for architectonic grammar reconstruction. (a) A general diagram, (b) table of diagram automation

The first automation level is ‘calibration.’ At this level, the whole grammar structure still comes from an experienced modeler’s manual work. The structure aims to reflect what components and primitives are there in the rough parameters of locations and sizes. The machine will do the parameters calibration, automatically. In this way, the human resource can be partially relieved from the laborious effort on fine-tuning the small digits in the parameters. Similar parameter optimization approaches are known well in the BIM performance fine-tuning (Asl et al. 2015) as well as HBIM (Bienvenido-Huertas et al. 2019). The saving will be more considerable if the parameters are interconnected—so that one small change in a parameter leads to impacts to another parameter.

The next level is ‘selection.’ A selection-level grammar reconstruction inherits the parameters automation part of the first level. Additionally, the components are selected automatically from an available library. For the manual work, the modelers first need to prepare a big enough component library—like the BIM component and resources libraries. Then, a sketch diagram of known relations of major unknown components can guide the machine to search for the best-fit instances in the library. On every trial, the first calibration level will be called to tell the best fitness. Overall, the machine runs in a trial-and-error fashion. For instance, Xue et al. (2019a) show that automatic ‘semantic registration’ of 8 furniture BIM components to a noisy point cloud. The semantic registration first performed such a ‘selection’ automation, then calibrated the three parameters, i.e., x, y, and heading direction. According to the experiments in Xue et al. (2019a), over 98% of modeling time was saved.

The ‘combination’ level elevates the selection level by evolving the components. Every as-designed component in the library consists of a system of geometric primitives. A combination-level automation machine evolves these primitives to the best-fit primitives through iterated evolutionary computation. For example, suppose the six sides of Wenge Pagoda in Figure 2a are slightly different (e.g, deformations within 5 mm), while the selected components by a Level-2 machine are perfectly symmetric. In that case, the Level-3 combination operation will try to select the related geometric primitives inside of the best-fit components for better fitting to the measurement. The combination-level reconstruction improves the accuracy of the Level-2 selection results.

The fully automatic level is classified as ‘Generation’ in this framework. The *a priori* setting of relations among major components is automated at this level. As a result, the relation modeling and arbitrarily new components are created by the machine rather than human export. However, a combinatorial explosion of the computational load growth is expected, due to the complicated and nested variables in the four levels. In the near future, the authors are not optimistic about seeing massive applications of this level to modeling cultural heritages.

The selection of an appropriate level can be based on the trade-off between marginal quality and cost. It means if both quality and cost are improved by an automated method, it is strongly recommended. Furthermore, the most recommended level is equipped with maximum bi-objective gains. Because usually, the quality may increase along with the automation level, while the cost is in the opposite direction. For example, Table 1 shows an assumed trade-off table for a company. When we use the “MIN()” function to measure the bottom-line gain, the ‘selection’ is the best level. The highest level may not be the best level. The authors wish to see progressive research and development in the next couple of decades, regarding the drivers and barriers. There is no need to target the highest level at the very beginning blindly.

Table 1. Example trade-off table and recommendation for a company

Level	Name	Quality gain (e.g., accuracy, innovation, semantics, etc.)	Cost gain (e.g., money, time, effort)	Recommendation (e.g., based on MIN(quality, cost))
1	Calibration	★	★★★	
2	Selection	★★	★★	✓
3	Combination	★★★	(Cost increased)	
4	Generation	★★★	(Cost increased)	

5 Conclusion

The automation of parametric and semantic HBIM reconstruction remains a very challenging topic to date. New schemas are desirable to improve this automation without increasing the cost. Architectonic grammar shows excellent potentials for HBIM reconstruction in recent studies. Therefore, we investigated a pilot case and a roadmap to inspire the future automation of architectonic grammar reconstruction from point clouds. The manual modeling of the selected Guangdong cultural heritages demonstrates how the architectonic grammars of the historic buildings can be organized as Grasshopper diagrams. Next, a roadmap described the four levels of automation is proposed. The quality improvement and cost of these four levels are also analyzed. Consequently, 'calibration' and 'selection' levels are recommended for practitioners based on the prospect of future research.

Following our roadmap, we will further investigate and develop the automatic 'calibration' and 'selection' methods based on architectonic grammar, and search for opportunities to attack the 'combination' and 'generation' levels of architectonic grammar reconstruction. Along with the architectonic grammar reconstruction, the geometric, semantic, and topological definitions in BIM and HBIM will be exploited and formulated. Moreover, advanced evolutionary computation algorithms and design knowledge suitable for solving such non-linear and expensive optimization problems, such as derivative-free optimization (DFO) and Gestalt principles (Xue et al. 2019b; 2020), will be employed in our automatic reconstruction.

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