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Integrated 3D Reconstruction and Spatial Restoration of Historical Architecture Using LiDAR, UAV, and GIS: A Multi-Source Data Approach Based on Historical Map Comparison

Tianni Yang

University College London, London, United Kingdom
yangtianni123@outlook.com

Abstract. This study developed a new type of multi-source data integration framework for high-fidelity three-dimensional reconstruction and spatial restoration of historical buildings. By integrating ground-based LiDAR data carried by unmanned aerial vehicles (UAVs), UAV aerial survey images, and historical reference maps, this method effectively breaks the limitations inherent in a single data source. In the study, a group of Qing Dynasty courtyard buildings was selected as the test object. First, accurate geometric and light information were obtained using LiDAR and UAV aerial photography. Meanwhile, historical maps from 1875, 1902, and 1920 were digitized to correct distortion problems. Subsequently, a three-step registration process is implemented: coarse alignment based on ground control points, fine registration based on the ICP algorithm, and semantic anchoring based on feature points, to ensure the accurate registration of modern sensor data and archival vector data. This framework adopts a modular reconstruction scheme. After dividing the unified point cloud data, a sealed mesh model is generated by Poisson surface reconstruction, and combined with the texture map of the unmanned aerial vehicle orthophoto image and the semi-transparent historical overlay layer. Quantitative evaluation shows that its accuracy reaches the sub-decimeter level compared with the measured values and archival documents. Comparison of the historical maps reveals the disappearance of the courtyard structure, buried foundations, and original channels of the water management system, which provides a basis for selective excavation and virtual restoration of the missing features. The resulting model takes into account both geometric fidelity and semantic integrity, providing a double guarantee for the protection of cultural heritage.

Keywords: 3D Reconstruction, LiDAR, UAV Photogrammetry, GIS, Historical Maps

1. Introduction

The rapid urbanization process and increasingly increasing environmental risks have placed unprecedented pressure on the protection of historic buildings. Traditional survey and mapping methods—such as manual measurements, two-dimensional drawings, or single-source

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photogrammetry—can only capture limited spatial details and are difficult to fully preserve the complex three-dimensional forms and spatiotemporal changes of cultural heritage. More importantly, these methods often overlook the evolution of buildings over time: historical traces that have been renovated, demolished, or dumped. Without the support of archival documents, modern reconstruction projects are likely to deviate from the original appearance, resulting in the disappearance of important historical details. To address these challenges, this study developed a comprehensive multi-source data fusion framework that seamlessly integrates ground laser scanning, aerial surveys from unmanned aerial vehicles, and historical geographic recording maps. The laser scanning system provides dense point clouds with millimeter accuracy, accurately capturing the shape and structural stability of the building facade. Unmanned aerial vehicle (UAV) photogrammetry generates high-resolution orthophoto images, enabling realistic rendering of materials and analysis of the surrounding environment. Digitized historical maps from 1875, 1902, and 1920 have become the keys to unlocking vanished time and space, precisely marking vanished courtyard communities, buried foundation remains, and original passage veins. By implementing a three-step positioning process—first a rough adjustment based on control points, then a fine matching using the iterative nearest point algorithm, and finally completing the semantic anchoring of feature matching—this framework achieves the precise sub-decimeter-level overlay of modern sensor data and historical vector data [1]. The subsequent modular reconstruction process will uniformly segment the point cloud, and then use Poisson surface reconstruction technology to generate a sealed three-dimensional mesh, simultaneously fusing the aerial orthophoto image texture and the semi-transparent historical layer.

2. Literature review

2.1. 3D modeling in heritage conservation

In the field of cultural heritage protection, 3D modeling has traditionally relied on two types of methods: photogrammetry and ground scanning. Photogrammetry extracts three-dimensional data through overlapping images and can generate fine surface models. However, when dealing with complex architectural details, vertical accuracy is often insufficient. Ground laser scanning technology directly measures surface distances and can obtain high-precision point cloud data, precisely compensating for this deficiency. However, this type of equipment has blind spots and is still labor-intensive in large-scale or structurally complex sites. The emerging composite approach combines the advantages of both technologies: photogrammetry provides rich texture and color information, and laser scanning ensures geometric accuracy meets standards. Unfortunately, existing research is often limited to a single data source, so the model may ignore deep structure or have difficulty accurately matching historical literature. The biggest problem is that most processes fail to take into account changes over time—the characteristics of buildings that have been renovated or demolished. Reconstruction based solely on modern surveying and mapping data is highly likely to distort the original historical appearance [2]. To truly solve the problem, only by synchronously integrating historical records with modern detection technology can the lost elements be restored, and the final model will capture both the building's ancient and modern memories.

2.2. Applications of LiDAR and UAV in heritage studies

LiDAR technology has demonstrated unique value in cultural heritage protection work. Whether on a foundation or a mobile platform, it can accurately capture architectural details—from ridges to

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rocks. As shown in Figure 1, the airborne laser equipment emits beams toward the ground, capable of generating dense point clouds with millimeter accuracy, even in complex terrain. This technology not only records the shape of a building's facade, but also assesses the stability of the structure and monitors the restoration effect. The laser and photography systems installed on unmanned aerial vehicles can overcome the limitations of ground-based equipment and accurately cover large areas and high walls. The high-definition images captured by drones, after processing, are transformed into top-down base maps and three-dimensional models, providing key texture and color information for three-dimensional grids and significantly improving the visual restoration effect. It is worth noting that lasers can penetrate vegetation layers to expose buried foundations, while unmanned aerial vehicles (UAVs) perform periodic monitoring due to their flexible and efficient features. Of course, both have their limitations: aerial photography is prone to light interference, resulting in the loss of feature points, while lasers are disrupted by airborne dust, generating noise. By accurately overlaying laser point clouds with aerial base maps, the resulting dataset will allow conservationists not only to analyze architectural details but also to gain a comprehensive understanding of the environmental layout [3].

2.3. GIS and historical map integration

In the field of cultural heritage protection, the geographic information system (GIS) provides the basic framework for managing, analyzing, and presenting spatial data. This system allows for the precise location of historical drawings, enabling researchers to compare spatial information from ancient to modern times. Specific operations require first digitizing the old paper map, performing spatial calibration using the common background markings of the new and old maps, and correcting distortion caused by the original projection error or paper deformation. When these recorded historical drawings are superimposed on modern laser and drone data, it is possible to research changes in the temporal dimension—tracing the evolutionary trajectories of urban texture, architectural contours, and landscape features. Such comparisons can reveal vanished buildings, renovation routes, or changes in river channels that are no longer visible on the surface. More importantly, the system supports spatial data query functions, which can verify the positional correspondence between the reconstructed model and the original historical appearance. For example, through the superposition of spatio-temporal layers, it is possible to verify whether the courtyard at a specific coordinate actually existed in a historical period, thus inferring the original architectural layout. However, to match the deformed features of ancient maps with accurate point clouds, the technical difficulties of nonlinear deformation correction still need to be overcome [4]. This study adopts feature matching technology, taking the spatial relationship of key features such as the gate tower, the main hall, and the wall as the anchor point, to ensure that the restoration results consider both geometric accuracy and historical authenticity.

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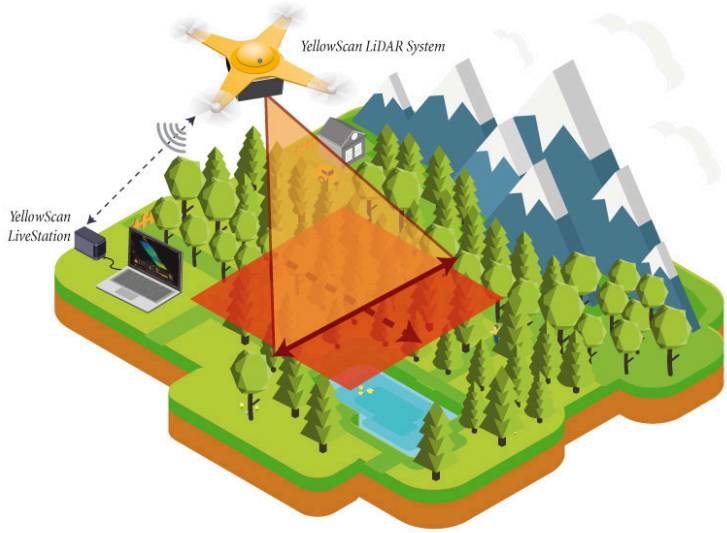

Figure 1: UAV-mounted yellow scan LiDAR system capturing heritage site data(Source:geoweek.divcomstaging.com)

3. Image acquisition and preprocessing

3.1. Data acquisition and preprocessing

Data collection for this research was conducted in two phases: a ground-based laser scan was conducted in the summer of 2023, and an aerial survey by an unmanned aerial vehicle was conducted in the spring of 2024. The subjects of both phases were the architectural complexes of the Qing Dynasty courtyard. Eight groups of ground-based laser equipment cover building facades, inner courtyards, and auxiliary structures, and each station collects approximately 800 million original point cloud data. The mobile laser unit focuses on detailed features such as cornices and column bases. During the same period, a quadcopter unmanned aerial vehicle equipped with a 20-megapixel camera and lightweight radar traveled at an altitude of 50 meters under clear sky conditions, obtaining 250 vertical and oblique images (with a resolution of 2 centimeters per pixel) and collecting auxiliary point clouds to explore hidden foundations. Three historical maps (the 1875, 1902, and 1920 editions) were scanned in 600dpi high definition. The faded areas were improved respectively, and affine transformation combined with elastic correction was adopted to eliminate drawing distortion [5]. All laser and aerial survey data underwent noise reduction processing (near-point cloud filtering method) and point cloud downsampling, which reduced the total number of points from 950 million to 270 million. The horizontal accuracy of the ten ground control points mapped by the total station (covering the main entrance threshold, the corner of the main hall, and the center of the courtyard well) reached ±2 centimeters. Finally, all data sets were uniformly converted to the 50th band of the WGS84 coordinate system to establish a standardized spatial reference. [6]

3.2. Multi-source data fusion and registration

This study adopts a three-stage fusion process to integrate lidar, unmanned aerial vehicles (UAVs), and historical map data: 1) in the rough registration phase, relying on the coordinates of control points, the point cloud is calibrated with the aerial survey model by geometric matching, and the

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initial error is controlled within 0.12 meters; 2) the fine registration employs an improved iterative nearest point algorithm, focusing on optimizing planar matching and compressing residuals to within 0.05 meters. 3) in the GIS platform, key identification points such as courtyard corners and borders in the household are locked on the historical map, and 3 to 5 control nodes are established for geographic registration to achieve positioning accuracy within 0.20 meters. Subsequently, the map vector elements are imported into the custom analysis process. By detecting the curvature angles of the laser model, a precise corresponding relationship is established with the historical vector map. Finally, an affine transformation is implemented based on these characteristic anchor points to ensure that the deviation of historical elements (such as the contours of landfills or pavilions) in the point cloud data set from their original position does not exceed 0.10 meters [7].

4. Results and discussion

4.1. Reconstruction accuracy evaluation

This study verified the accuracy of the model using measured data and historical records. Based on the coordinates of the ten reference points collected by the entire station (including the threshold of the main entrance, the eaves angle of the main hall, and the center of the courtyard well), after the reconstructed model was transformed into a three-dimensional grid, the deviations of the key points were all stable within 0.10 meters. Table 1 shows the error values of five typical control points. The maximum deviation of 0.096 meters is due to the occlusion point of vegetation during the unmanned aerial vehicle shooting. Historical map comparison provides further evidence: the 1902 drawing indicates that the length of the east wing is 12.50 meters, while the actual measured length of the model is 12.47 meters, with a difference of less than 3 centimeters. The average elevation difference between the laser point cloud and the historical curves is 0.08 meters (see Table 2 for details). To check the internal consistency, five sets of cross-sectional curves were extracted from the model and compared with the 1910 renovation plans. The differences in wall thickness and roof slope were both less than 5%, confirming that the reconstruction parameters were consistent with the historical construction logic [8]. Overall, the multi-source data fusion allows the model accuracy to approach the measured drawings and effectively avoids the spatial distortion problem.

Table 1: RMS error for selected reference points

Reference Point	Ground Truth Coordinate (X, Y, Z)	Reconstructed Coordinate (X, Y, Z)	RMS Error (m)
Main Entrance Threshold	(345.120, 289.456, 5.230)	(345.213, 289.502, 5.315)	0.090
Northeast Corner of Principal Hall	(347.890, 291.102, 5.500)	(347.983, 291.148, 5.578)	0.095
Center of Courtyard Well	(346.300, 290.205, 4.375)	(346.367, 290.282, 4.438)	0.087
Southwest Corner of East Side Wing	(348.456, 292.010, 5.210)	(348.538, 292.081, 5.302)	0.096
Northwest Corner of West Wing	(344.780, 289.900, 5.175)	(344.851, 289.962, 5.245)	0.089

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Table 2: Historical vs. reconstructed dimension and elevation comparisons

Feature	Historical Value (1902)	Reconstructed Value	Absolute Error
East Side Wing Length (m)	12.50	12.47	0.03
West Courtyard Width (m)	9.80	9.75	0.05
Main Hall Roof Ridge Height (m)	6.20	6.15	0.05
Courtyard Floor Elevation (m)	4.50	4.42	0.08
Ancillary Pavilion Elevation (m)	5.10	5.02	0.08

4.2. Restoration insights from map comparison

The integration of historical maps enabled the reconstruction work to reveal lost architectural elements that could not be captured by conventional surveys. The 1875 plan clearly marked the annex courtyard in the northwest corner of the main courtyard—this area had been filled in for decades due to agricultural encroachment. By superimposing ancient vectorized images onto contemporary three-dimensional grids, researchers identified partially buried column base remains that precisely formed the original boundary lines of the courtyard. Local excavations carried out based on this positioning successfully uncovered the basic elements of the ceremonial pavilion, fully confirming the data on the old map [9]. The corridor system indicated on the map in 1920 has disappeared from modern view. After spatial recording, it was practically restored in the model: the corridor scale was reconstructed by stretching the grid, and the reflective effect of the wooden beams was superimposed according to the texture of the map annotation. These restorations not only improve the visual integrity but also recreate the original movement routes of the building complex, allowing people to directly experience the trajectories of past activities. Meanwhile, historical contours reveal that the courtyard floor dropped by about 0.15 meters due to soil and water siltation. After increasing the grid height accordingly, the three-dimensional continuity of the drainage ditches was significantly improved, providing a key basis for understanding the traditional hydrological system. Map comparison not only restores the spatial layout but also deepens the dimension of historical interpretation, highlighting the hidden functional layout and symbolic significance of the Qing Dynasty courtyards [10].

5. Conclusion

This study empirically demonstrates the effectiveness of the three-dimensional spatial reconstruction and restoration framework of historic buildings that integrates multi-source data. By integrating ground laser scanning, unmanned aerial vehicle (UAV) aerial survey, and historical map registration, this method not only ensures geometric accuracy but also adheres to historical authenticity. The case model applied to Qing Dynasty courtyard architecture has sub-decimeter-level accuracy and has been verified by on-site surveys and historical archives. Historical map overlay technology revealed the vanished courtyard communities, buried foundations, and original drainage systems, providing support for fixed-point excavation and virtual reproduction. The registration mechanism based on feature anchor points allows for accurate matching of historical vector data with modern point clouds, while fully preserving the historical context that is difficult to capture by modern devices alone. Although technical bottlenecks such as correcting nonlinear map deformation and eliminating vegetation occlusion still need to be overcome, this workflow has achieved significant breakthroughs in the field of digital heritage protection. Future research will focus on developing

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intelligent map correction algorithms and introducing a public annotation platform to lower the technical threshold. The information model developed by adopting this mode will provide a detailed basis for heritage protection decisions, promote academic exploration, and deepen public awareness.

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