Heritage Science

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Application of 3D laser scanning technology for mapping and accuracy assessment of the point cloud model for the Great Achievement Palace heritage building

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Abstract

Heritage buildings represent history and act as vessels of human civilisation. The significance of these architectural phenomena increases as society increases, which renders their preservation and ethical use increasingly crucial. Hence, preserving heritage buildings is necessary for societal benefit. The accuracy of three-dimensional (3D) point cloud models of heritage buildings is important to their digital conservation. Traditional mapping methods typically require more time and human resources. Furthermore, the outcome is subject to measurement omissions, errors, and other issues, which are contrary to the protection of the object measured. The complex elements of ancient Chinese architecture render it challenging for traditional measuring techniques to accurately capture spatial structural information. The 3D laser scanning technology is a novel technology to obtain 3D data rapidly. In this paper, the Great Achievement Palace of the Confucian Temple in Yuci District, Jinzhong City, Shanxi Province, was used as an example to examine the application of 3D laser scanning technology to acquire point cloud models of heritage buildings. Field data collection for architectural heritage using 3D laser scanning technology requires measuring station setting analysis to ensure effect accuracy while considering the elements of target location and quantity. For the 3D point cloud model of the Great Achievement Palace, error analysis and accuracy assessment were conducted on the quality elements of alignment accuracy between scanning stations, point cloud model reliability, point cloud data noise condition, and whether the point cloud data were stratified. The findings demonstrated that the improved method quickly and accurately acquired 3D point cloud model data and obtained realistic spatial data models of the heritage building.

Keywords Heritage building, Laser scanner, 3D point cloud model, Model accuracy

Introduction

The heritage building is a representation of the magnificent culture generated by the intelligent and talented Chinese people [1]. Poor upkeep and management is a persistent issue regarding heritage buildings globally. In the technologically advanced modern world, the construction business is developing rapidly and markedly due to the expanding field of information-driven developments. Hence, there are substantial quantities of themed structures, and several new skyscrapers have appeared. Nevertheless, historic Chinese structures are disappearing despite the fact that heritage buildings are an artistic representation of history. Studying legacy architecture enables the thorough analysis and appraisal of historical societies, cultures, aesthetics, and politics [2]. Furthermore, 3D-based environments, create digital pairs of the

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physical world and provide an immersive experience to users with technological competencies supporting daily and social activities [3, 4].

Chinese heritage buildings differ from that of other regions as timber is the predominant primary building material [5]. Nonetheless, timber decays easily and its destruction is directly because most current existing historical buildings in China are from the Ming and Qing Dynasties, with extremely few wooden buildings from the Tang and Song Dynasties. Furthermore, many of these historical buildings (buildings constructed during the Ming dynasty), are in disrepair and on the verge of destruction [6]. The structural complexity of ancient Chinese buildings is a significant factor for consideration. The severe lack of surveyors with specialist knowledge of ancient architecture has resulted in the current numerous incomplete basic drawings of traditional Chinese buildings and inaccurate existing artwork. These aforementioned inadequacies are extremely detrimental to sequential maintenance, repair work, and scientific restoration work.

Preserving and studying architectural heritage is challenging but necessary for proper conservation of traditional structures and ancient artifacts. The original appearance of heritage buildings should be recorded by a three-dimensional (3D) point cloud model of ancient buildings, thus providing basic data on traditional architecture for heritage repair, maintenance, and conservation [7]. Due to its contactless, rapid, accurate, and efficient information collection capabilities, 3D laser scanning measurement technology has proven to be highly efficient and effective for preserving and restoring Chinese heritage buildings.

The Yuci Confucian Temple on the north of Longwangmiao Street in Yuci City (Jinzhong City, Shanxi Province) is the oldest surviving building in the city, and is also a municipal-level cultural relic protection unit [8]. In 2004, the Yuci District repaired and rebuilt the Temple of Literature, which covered an area of 23,000 square meters with a building area of 6000 square meters. Generally, the Temple of Literature is dedicated to Confucius, who was a notable Chinese educator and statesperson who established the Confucian school of thought 2560 years ago. The Temple of Literature is also the seat of the local school palace and office of the Confucian schoolmaster throughout Chinese history. Undoubtedly, the Yuci Confucian Temple represents and symbolises Confucian cultural origins[9].

Containing nine columns in the front and comprising five chambers, the Great Achievement Palace of Yuci Confucian Temple is the primary temple structure and features the greatest architectural and construction standards. The double eaves and remaining structures are on the hilltop. Twenty-eight precisely placed dragon stone columns are arranged symmetrically, and showcase the architectural beauty. The hall houses many statues of Confucius, four philosophers, and 12 wise men. The walls on either side of the hall feature 24 pictures of filial piety and a plaque written by Qing Dynasty emperors. Thus, the building data of the Great Achievement Palace, which is a specific symbol of Chinese civilisation, necessitates preservation by the point cloud model.

Ensuring fine-grained 3D point cloud model data is necessary to preserve, maintain, or restore an architectural heritage [10]. Traditionally, ancient buildings were designed using simple surveying tools, which yielded only two-dimensional drawings and written records [11]. Total station surveys are exclusively applicable for single-point data acquisition, which is time-consuming and challenging for traditional building surveys. Additionally, the subsequent data processing is complex. Contrastingly, close-range photogrammetry acquires data on the subject via photography. Nevertheless, directly obtaining a 3D model is not possible practically as it requires matching and calculating the received pictures. The 3D laser scanning advanced technology enables point cloud data acquisition and the generation of 3D point cloud models that realistically portray the overall structural and morphological characteristics of the target. Laser scanners easily measure the direct 3D coordinates of numerous points in a shorter duration [12]. Furthermore, laser scanning acquires the complete spatial information of a traditional building and preserves the most comprehensive reference material and documentation. In heritage building preservation, 3D laser scanning is extremely precise and reliable while capturing data for point cloud model construction. The most common laser scanning outcome is a point cloud: a set of points in 3D space defined by their coordinates and composing a 3D representation of the scanned object [13].

The aforementioned findings highlight the exceptional accuracy achieved through on-site data collection and the development of high-precision models for historic structures. This achievement is of significant substantial importance for guiding heritage building preservation and appropriate use. The availability of precise and detailed information obtained via 3D laser scanning contributes significantly to informed decision-making and effective planning regarding these valuable architectural treasures.

Literature review

The works created by previous generations and believed to have universal values are generally termed cultural heritage [14]. The People's Republic of China Cultural Relics Protection Law, Article II clarifies the following areas of importance regarding cultural relics, which include heritage buildings: historical importance, artistic value, and scientific relevance [15]. Heritage buildings are material and spiritual representations of human civilisation and are rare and non-renewable. While effective protection preserves and sustains heritage originality, heritage buildings that are improperly protected or destroyed will be lost permanently. Therefore, heritage buildings are typically protected and are of symbolic importance [16]. Cultural heritage studies frequently require the research of structures that have undergone several modifications throughout their existence. Typically, such modifications refer to the demolition of architectural components and the addition of new structural elements that alter the earlier structural properties. Thus, virtual reconstruction is a vital and essential component of numerous scientific and cultural applications to recover missing building block structures [17].

Both terrestrial and airborne laser scanning are possibly the best and most important surveying technology developed over the previous 20 years [18]. The use of laser scanning to produce dense point clouds for documentation, mapping, and multi-scale viewing evolved during the 20-year period, and is now a standard approach [17]. Tangible digitalisation utilises automatic reconstruction 3D modelling techniques, such as 3D laser scanning and photogrammetry. The 3D laser scanning is an advanced technical solution used for exact analysis and the complete demonstration of items via 3D reconstruction [19]. A comprehensive 3D model can be acquired easily from multiple shots obtained from different directions that provide data from all sides of the building. Merging these scans into a cohesive reference system aligns and combines the information received from all sites and results in the development of a complete model in a single file [20].

The 3D laser acquisition standards originate from the accuracy directions of the 3D laser, the layout of the control network corresponding to the global positioning system (GPS) geodesic coordinates, optimal analysis of 3D laser scanning station deployment, and suitable instrument selection for 3D laser scanners [21]. The application of the method by Alessandra Capolupo involved two high-quality 3D point clouds of the Monastery of St. Claire (Bari, Southern Italy), which were generated using two competing survey techniques: the remotely piloted aircraft system (RPAS) structure from motion (SfM) and multi-view stereo (MVS) technique, and terrestrial laser scanning (TLS). Subsequently, the correctness of the geometric characteristics collected using the RPAS digital photogrammetric and TLS models was analysed and reported [22]. Other researchers focused on evaluating the accuracy of geometric feature points regarding noise. This study is an omnidirectional study from 3D data acquisition to data processing, and involves the aspects of alignment accuracy, point cloud model reliability, noise conditions, and point cloud data stratifications.

Method

This study used 3D laser scanning technology to perform precise 3D scanning measurements of the Great Achievement Palace building. The use of architectural scanning technology enabled thorough examination and development of both the exteriors and interiors of the heritage building. The information collected was analysed and compared to ensure the accuracy of the heritage building digital picture, which enabled a thorough understanding of its architectural features and permitted informed conservation and preservation operations.

The research strategy consisted of three stages (see Fig. 1). First, 3D point cloud data and images of the building were obtained with a 3D laser scanner (Leica ScanStation P40). The main aim of collecting the primary data was to identify and scan the visual information of the building. Second, the point cloud was processed to derive a model of the building with complete data. Third, the model data was used to analyse the model accuracy errors and assess the modelling accuracy according to current standards.

Data collection outdoors

Throughout the equipment selection process, it was essential that high-precision measuring instruments were selected with care to ensure the most precise historical and architectural data. The Leica ScanStation P40 used to obtain the Great Achievement Palace model data involved a scanning rate of up to 1,000,000 points/s, high distance measurement accuracy and angular accuracy, a horizontal and vertical field of view of 360° and 270°, respectively, and effective scanning distance of 270 m@34% reflectivity, which obtained more data from fewer sites for the analysis. The software used for this purpose was Leica Cyclone [23]. In the distance measurement system, the laser emission angle was <0.23 mrad while the front window laser spot diameter was ≤3.5 mm.

The 3D laser scanning technology is based on laser beam emission, and the time involved is measured by the subsequent measurement of the duration required for the reflected laser light to return. Distance measurement is facilitated when it is based on the speed of light. For data acquisition, the laser scanning system

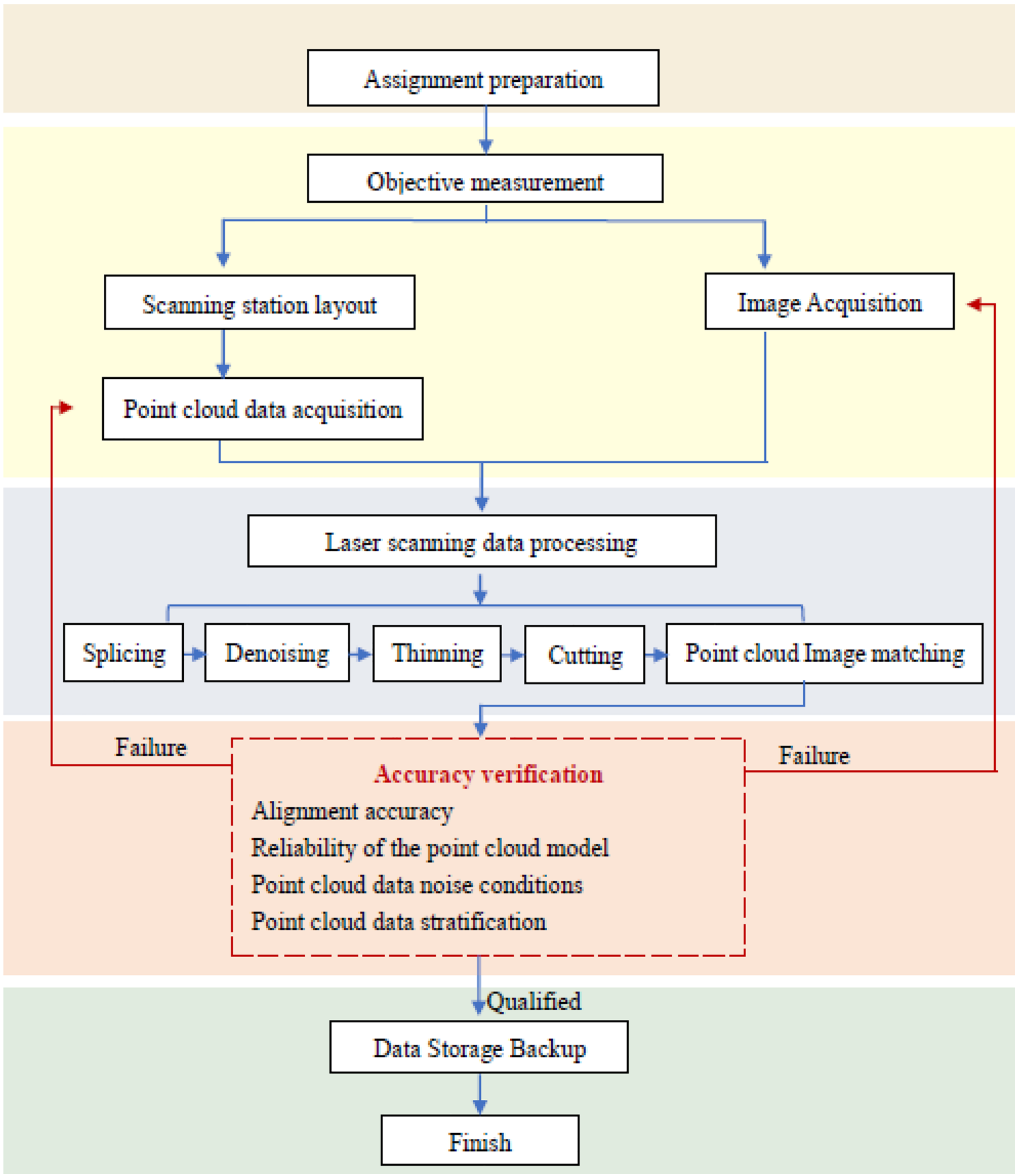

Fig. 1 Flowchart

emits an amplitude-modulated laser beam and receives the reflected laser, which measures the phase difference between the projected and reflected rays to calculate the distance. Furthermore, the 3D laser scanner rotates rapidly, which enables efficient laser beam emission and range in multiple directions. This advanced functionality enables the rapid acquisition of a comprehensive 3D point cloud model, and encompasses intricate details and precise spatial information. A time counter accurately records the process duration, which enables calculation of the distance between the scanner and the target point using the formula $S = 1/2ct$ (c represents the speed of light and t is the time elapsed). Each sensor records the laser emission angle, and the target point X, Y, and Z coordinates are determined using the interconversion between the polar and Cartesian coordinate systems. Hundreds of millions of coordinates, which each have corresponding 3D coordinates and reflectivity information, are subsequently processed and rendered on a computer, and result in an accurate and comprehensive depiction of the surrounding environment. Known for its advanced and precise capabilities, 3D laser scanning technology is frequently referred to as real-world replication.

Fig. 2 Side view of the Great Achievement Palace

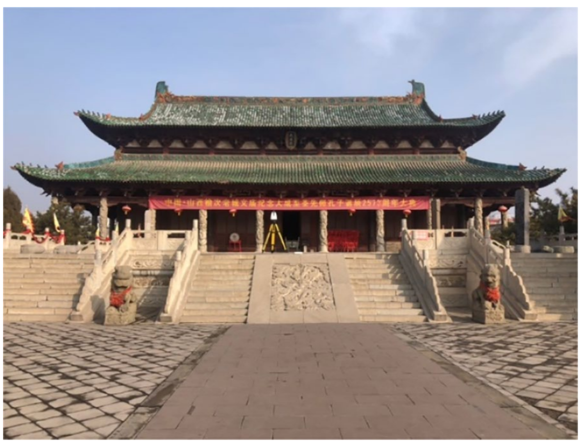

Fig. 3 Front of the Great Achievement Palace

The data were collected as a field scan, where measurement locations, targets, and scanning accuracy were established to obtain a data point cloud. As many historic buildings are more angular and complex, it is reasonable to establish multiple measurement points and targets by scanning in more stations and directions to avoid excluding sections due to too many cloud points. The side and front views of the Great Achievement Palace are depicted in Figs. 2 and 3, respectively.

After creating a new project, the level and laser alignment are adjusted in the status menu before scanning. In the scan field of view, either by panoramic scanning or setting the view angle area for the scan field of view, for example, the station 4 field of view was set to 21.358°–163.089° and the station 5 field of view starting angle range was 262.652°–268.611°. Station 6 had an area of view angle range of 262.620°–350.512°. The precise adjustment of the angle relies on the station positioning and structure size. The field of view configuration is significant in ensuring the accuracy and completeness of the target object mapping data. The configuration used in this study is depicted in Fig. 4.

Sixteen stations were established when scanning the Great Achievement Palace. A feasible target layout was necessary to enable multiple stations to examine points with different coordinates in the point cloud model aligned to the same coordinate system and obtain complete surface information of the object shape. As adequate data coverage is required to fulfil the authentication and integrity requirements of 3D information acquisition for historical building conservation and restoration, the scanning locations were arranged to cover individual heritage structures. The basic methodology or principles were as follows: first, three targets were aligned in a non-linear configuration between every two sites. Second, the survey target locations should adhere to the principle of serving the site, which involved setting the targets in a coordinated manner to scan as many sites as possible. This approach aided the minimisation of the number of objects required and reduced point cloud errors when processing multiple buildings. Third, the setup (see Fig. 5) should avoid missing established targets.

As scanning accuracy settings affect the final results of historic building mapping, using low- to

Fig. 4 The Great Achievement Palace station 4.5.6 field of view setting

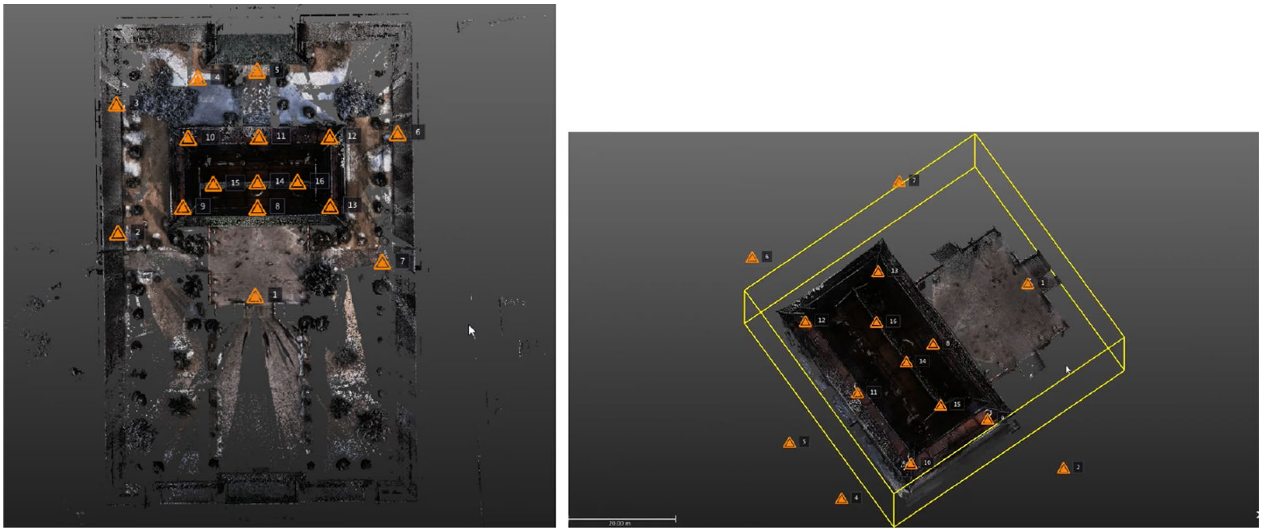

Fig. 5 Setting up of the Great Achievement Palace scanning site

medium-resolution scanning is a common practice to position the measurements of groups of buildings and the dimensions of single buildings. Nonetheless, precise scanning is required for specific detailed components of historic buildings, such as plaques, lettering, or painted motifs. Therefore, high-resolution scanning is used to obtain results. For image configuration, pixels are examined by the image controller settings. The image pixels set for this study were 960 × 960 for the study object. The size image pixel size affects the point cloud model resolution. The panoramic picture data collection approach fulfils the requirement of capturing the characteristics of the interior areas, and results in a complete visualisation.

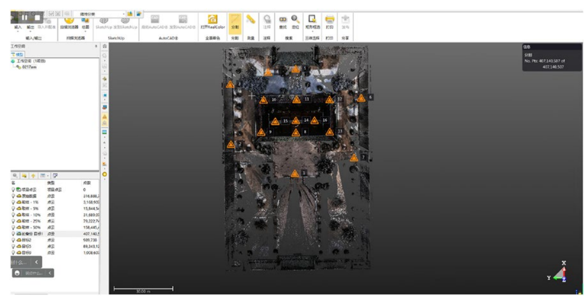

Fig. 6 Before splicing

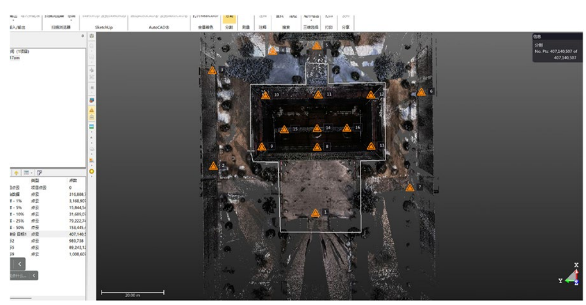

Fig. 7 After splicing

Model data processing

Data processing is vital in 3D laser scanning, and mainly involves data stitching, denoising, segmentation, and point cloud image matching. In heritage building conservation and research, 3D laser scanning has the remarkable advantages of reducing information retention time and improving information accuracy. Simultaneously, the decorative elements and patterns of heritage buildings require high clarity. Therefore, accurate data splicing is a significant issue under investigation in 3D modelling. Trimble RealWorks point cloud processing software automatically executes point cloud splicing and known points splicing. The splicing result accuracy determines the point cloud model accuracy. The models before and after splicing are depicted in Figs. 6 and 7, respectively.

The factors of the scanning environment and instrumentation result in unavoidable external noise in point cloud data, which must be removed during data processing to obtain more accurate data on the object to be analysed. After a complete point cloud has been constructed, unnecessary information, such as people, equipment, surrounding buildings, trees, debris, or noise, should be avoided. Accordingly, the point cloud data must be filtered and denoised. Importing the point cloud data into Trimble RealWorks [24] enables manual removal of the more obvious noisy points, such as floating points in the air or unique protruding points, which are generally distinct from the body of the point cloud. A filtering operation can eliminate the noise at points close to the point cloud body.

To remove objects with unique shapes in cluttered point clouds or to process model monoliths, proximity-based point cloud segmentation divides point clouds into regions based on their proximity information. The before and after splicing models are depicted in Figs. 8 and 9, respectively, and the cutaway view is depicted in Fig. 10. Compression methods can accelerate data processing and maximise storage utilisation without compromising surface reconstruction or clarity criteria.

The Leica 3D scanner combines a laser scanning sensor with an image camera through high dynamic range

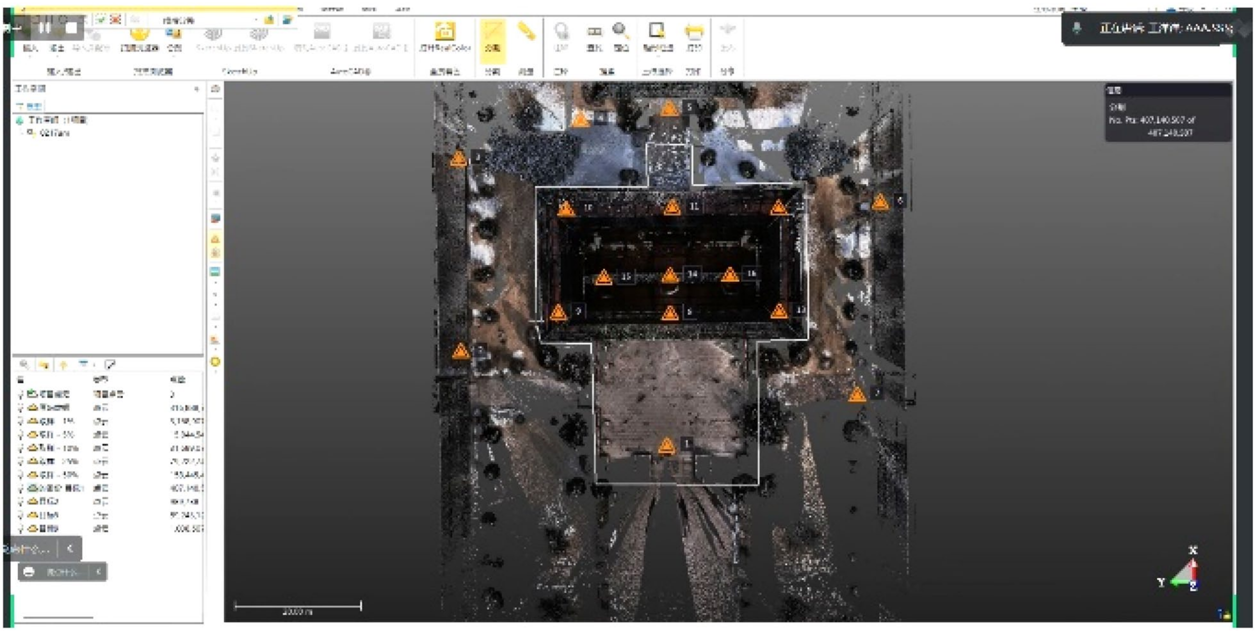

Fig. 8 Before splitting

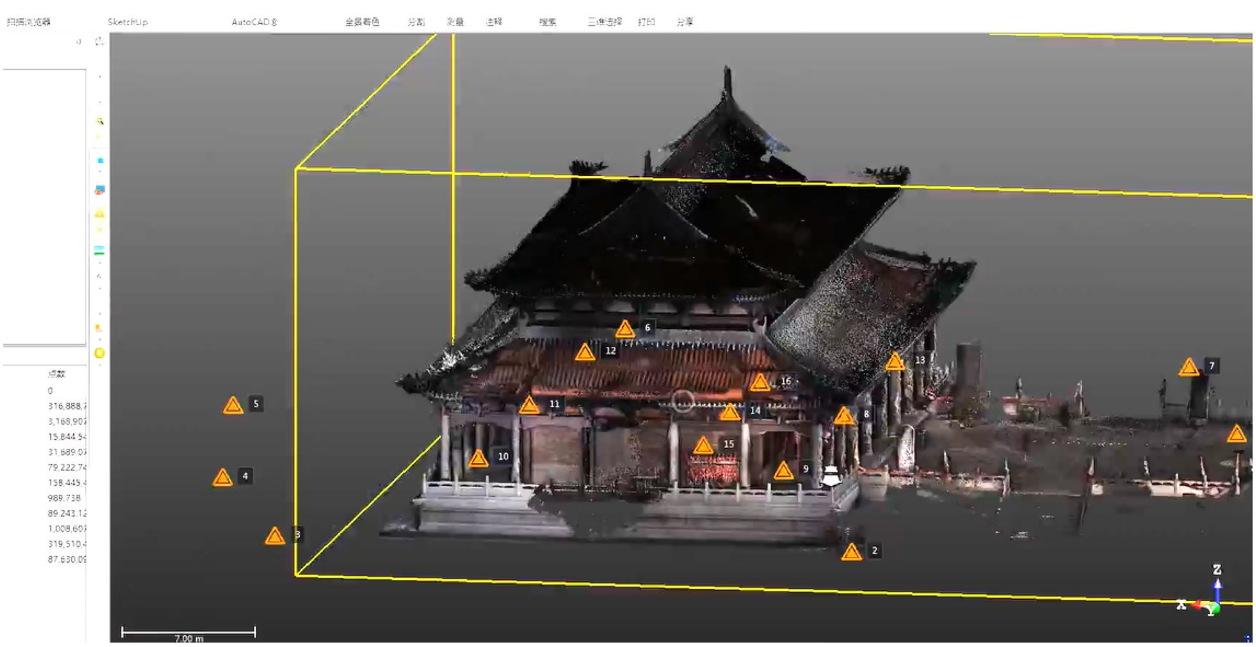

Fig. 9 After splitting

(HDR) image technology and mixed pixel technology to match the point cloud to the image, which enables the extraction of detailed colour information from the point cloud while ensuring clarity. The point cloud model is presented in Fig. 11. The quality control elements of digital mapping results generally depend on positional accuracy, dimensional accuracy, integrity, and logical consistency. Terrestrial 3D laser scanning technical specifications specify that the accuracy and technical specifications of terrestrial 3D laser scanning point clouds should meet the requirements stated in Table 1.

The specifications for 3D geographic information model data products (CH/T 9015-2012), Technical Standard for Ground 3D Laser Scanning Operations (CH/Z3017-2015) [25], Specification for Ancient Building Surveying and Mapping (CH/T 6005-2018) [26], Specification for 3D Laser Scanning of Cave Temples (DB14/T 1926-2019) [27], Technical Standard for Digitalisation of Historic Buildings (JGJ/T 489-2021) [28], other existing standards and specifications, the technical standard for data collection and processing criteria for indoor 3D geographic data, and many other standards for cultural relic modelling state the following aspects control accuracy: the quality elements are alignment accuracy between scanning stations, point cloud model reliability, point cloud data noise condition, and point cloud data examination for classification. The 3D point cloud model accuracy was analysed based on stitching reports, dimensional accuracy, point cloud thickness, and observation of point cloud model layering.

Accuracy assessment and error analysis

Quality control elements of digital mapping results generally depend upon factors like positional accuracy, dimensional accuracy, integrity, logical consistency, and more. According to the technical specifications for terrestrial three-dimensional laser scanning, the accuracy and technical specifications of terrestrial three-dimensional laser scanning point clouds should meet the requirements of Table 1. In the $CH/Z3017-2015$ specification, the sections highlighted in gray in Table 1 provide the basis for the range of dimensional accuracy errors and standards discussed in "Point cloud model reliability" section of this paper.

In the CH/T 6005-2018 specification, the sections highlighted in gray in Table 2 provide the basis for determining whether the dimensional accuracy errors discussed in "Point cloud model reliability" section of this study meet the accuracy standards. Specifications for the digital products of three-dimensional model on geographic information are given in CH/T 9015-2012. Specification for ancient building surveying and mapping are described in CH/T 6005-2018. Specification for three-dimensional laser scanning of cave temples are given in DB14/T 1926-2019. The DB14/T 1926-2019 specification provides technical guidance for the alignment accuracy

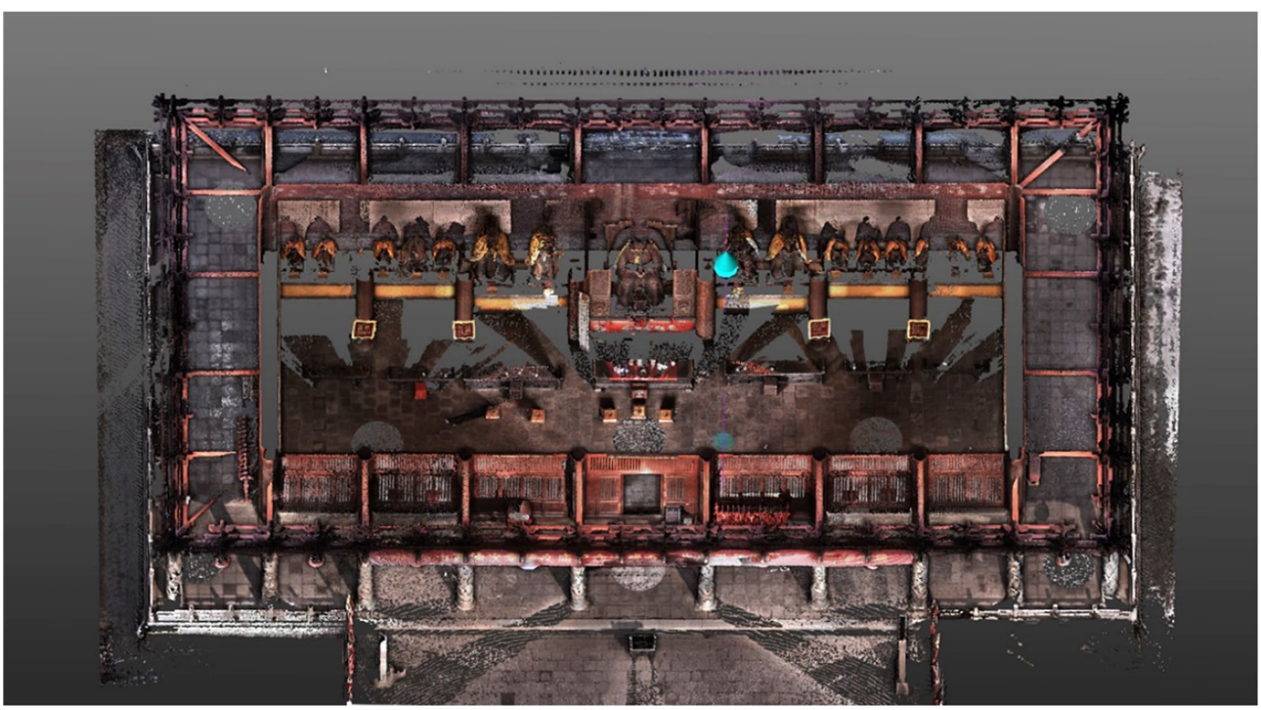

Fig. 10 Cutaway view of the Great Achievement Palace

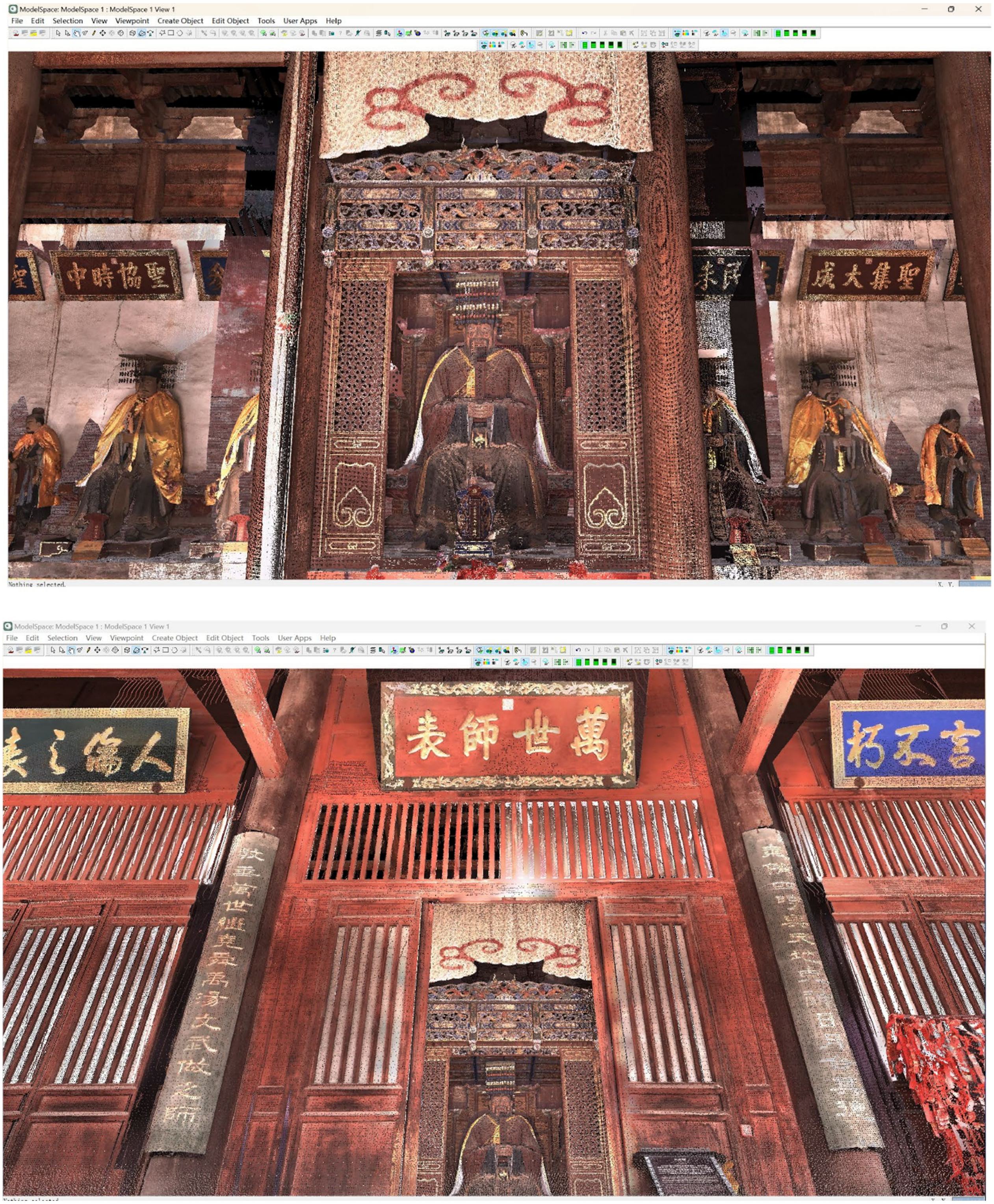

Fig. 11 Point cloud model of The Great Achievement Palace

Table 1 Terrestrial 3D laser scanning point cloud accuracy and technical specifications ($CH - Z3017 - 2015$)

Level	Medium error in feature point spacing (mm)	Error in point position relative to adjacent control points(mm)	Maximum point spacing (mm)
Grade 1	≤5	–	≤3
Grade 2	≤15	≤30	≤10
Grade 3	≤50	≤100	≤25
Grade 4	≤200	≤250	–

Table 2 Point cloud accuracy and technical specifications ($CH/T6005 - 2018$)

Level	Medium error in feature point spacing (mm)	Error in point position relative to adjacent control points(mm)	Maximum point spacing(mm)
Grade 1	≤ 5	–	≤ 5
Grade 2	≤10	≤ 30	≤ 10
Grade 3	≤ 25	≤ 100	≤ 25

between scanning stations discussed in section "Alignment accuracy between scanning stations" and the point cloud data noise situation discussed in section "Point cloud data noise" of this paper. It emphasizes quality control for key aspects of point cloud data registration, denoising, and thinning accuracy. The overlap between point clouds from adjacent scanning stations should not be less than 30% and when there are outlier points or isolated points in the point cloud data that deviate from the scanned target objects, filtering methods or manual denoising should be applied based on the quantity of points. Lastly, the technical standard for digitalization of historic building is mentioned in JGJ/T 489-2021 which mentions that For digitization of Grade I and Grade II historical buildings, the mean error between feature points should be less than 20 mm and 50 mm for Grade III.

The 3D model inspection quality elements and details are listed in Table 3.

Alignment accuracy between scanning stations

The cloud data of the 16 stations were evaluated using Trimble RealWorks [24]. The alignment report (using TZF scans) determined that nine similar point stations had less than 30% overlap, while the remaining 34 point stations had greater than 30% overlap. The average inter-site scan overlap was 41.65, which agreed with the overlap quality standard of greater than 30%. The mean reliability was 93.79%, whereas the mean error for the 16 stations was 2.26 mm. The splicing report is presented in Table 4.

Point cloud model reliability

To assess the scanning accuracy and errors of the Great Achievement Palace decoration elements, the dimensions of the wooden window decoration on the left side of the front door of the building and the stone balustrade decorative element were randomly chosen and compared with the 3D laser scan data using vernier callipers and tape measures. The allowable deviation of timber structure production and comparison of the dimensional accuracy are reported in Tables 5 and 6, respectively. On-site measurements are depicted in Fig. 12, and a 3D drawing of the building in the software is depicted in Fig. 13.

The aforementioned comparison of the window dimensional accuracy with the 3D point cloud data revealed that the average error was 1.41 mm, where the expected accuracy of the panel width and height was 2 mm. Therefore, the average accuracy met the accuracy standard in the Allowable Deviation of Timber Structure Production

Table 3 3D model inspection quality elements and details

Point cloud model correcteness	Quality elements	Details of the inspection	Standard
	Alignment accuracy between scanning stations	Splicing report	DB14/T 1926-2019 [27]
	Reliability of point cloud models	Dimensional accuracy	CH/T 9015-2012 [29], CH/Z3017-2015 [25], CH/T 6005-2018 [26], JGJ/T 489-2021 [28]
	Point cloud data noise conditions	Thickness of point cloud	DB14/T 1926-2019 [27]
	Stratification of the point cloud model	Point cloud model layering situation	CH/Z 3017-2015 [25]

Table 4 Splicing report

Site	Object Stations with common points	Error (mm)	Overlap (%)	Reliability (%)
1	8	1.19	48	98
	9	2.86	25	88
2	3	5.45	28	86
	8	3.02	35	92
	9	1.77	42	93
3	6	8.21	32	87
	10	4.09	30	91
4	5	0.9	55	99
	10	1.72	31	93
	11	2.51	32	93
5	4	0.9	55	99
	11	1.11	42	98
6	3	3.21	32	87
	9	6.28	29	81
7	13	3.08	21	82
8	1	1.19	48	98
	9	1.8	40	97
	13	1.67	41	97
9	1	2.86	25	88
	6	8.28	29	81
	8	1.8	40	97
	10	1.54	38	96
10	3	4.09	30	91
	4	1.72	31	93
	9	1.54	38	96
	11	0.8	50	99
	12	2.1	28	91
11	4	2.51	32	93
	5	1.11	42	98
	10	0.8	50	99
	12	0.99	48	98
12	10	2.1	28	91
	11	0.99	48	98
	13	1.22	39	97
13	7	3.08	21	82
	8	1.67	41	97
	12	1.22	39	97
14	15	0.69	75	99
	16	0.75	76	99
15	14	0.69	75	99
	16	1.45	63	98
16	14	0.75	76	99
	15	1.45	63	98
Average		2.26	41.65	93.79

Table 5 Allowable deviation of timber structure production

Number of entries	Projects		Permissible deviations(mm)
1	Section sizes of components	Width and height of square timber elements	−3
		Plate width and height	−2
		Tip diameter of log elements	−5
2	Length of components	Length greater than 15 metres	±10
		Length less than 15 metres	±15

Table 6 Comparison of the dimensional accuracy of the Vernier calipers/tape measure and 3D point cloud data for the windows of the wooden elements to the left of the front door of the Great Achievement Palace

Objectives	3D point cloud dimensions (mm)	Vernier calipers (mm)	Tape measurements (mm)	Deviation (mm)
1	118.23	120.75	–	2.52
2	80.33	78.78	–	1.55
3	49.69	49.99	–	0.3
4	79.77	79.86	–	0.09
5	151.84	152.2	–	0.36
6	660.96	–	658	2.96
7	747.07	–	745	2.07

Fig. 12 Vernier calipers for on-site measurements

document in these three groups. The reason is that the decorative elements had sparse point cloud density. The scanning station numbers should increase when the decorative element model is acquired, while the point cloud density ensures that the point cloud model dimensional accuracy meets the requirements (see Table 1).

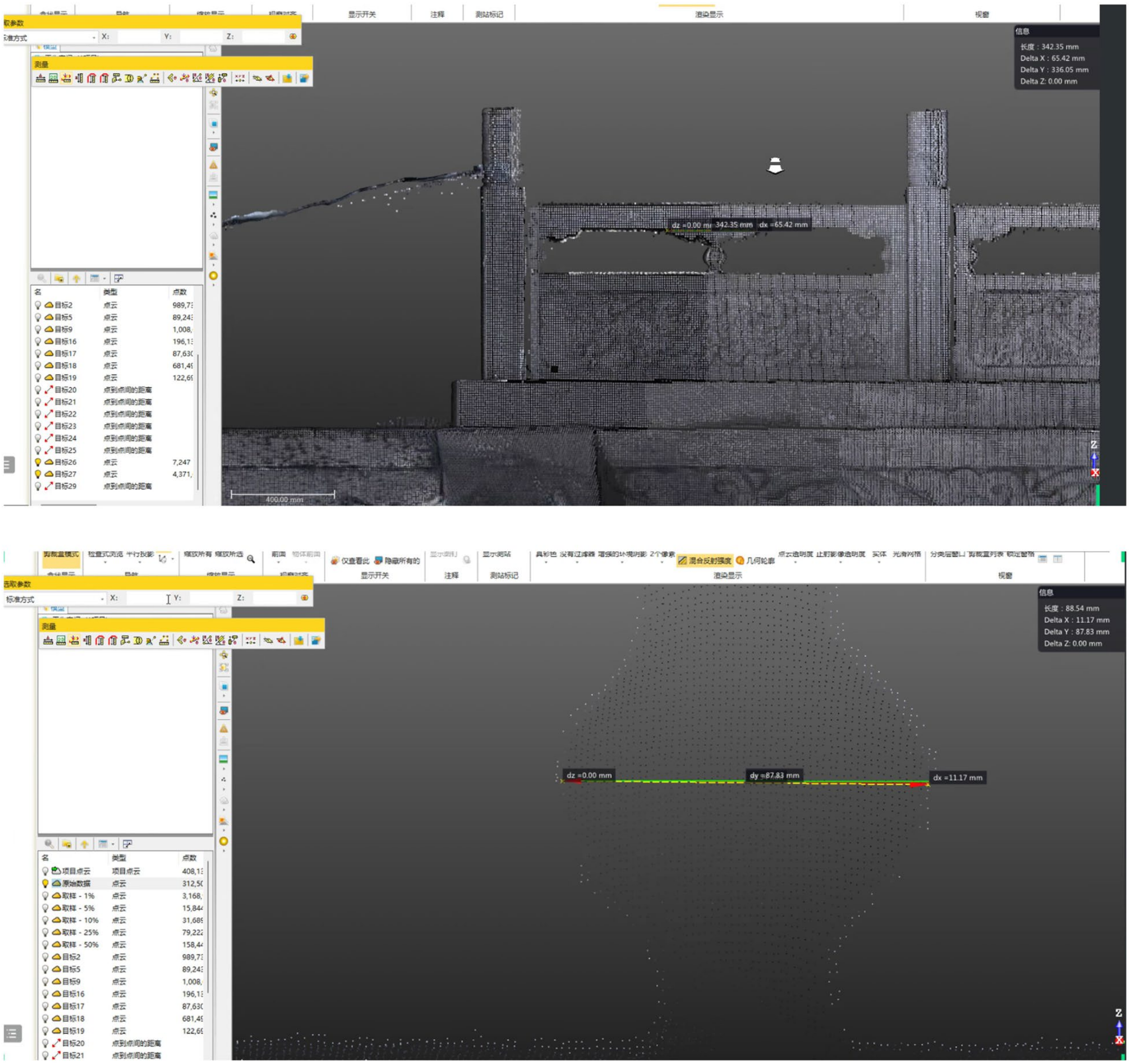

Fig. 13 Dimensional drawing of the Great Achievement Palace balustrade in Trimble Realworks software

The comparison of the manual measurement and the 3D point cloud data is reported in Table 7.

The average error of the point cloud model of the stone balustrade was 1.045 mm, and the dimensional accuracy of that decorative element met the point cloud model quality requirements. The stone decorative element was represented at stations 4, 5, 11, and 12, specifically the nearest straight-line distance between station 11 and 12,

Table 7 Comparison of vernier calipers or tape measures with 3D point cloud data for stone decorative element balustrades

Objectives	Balustrade components	3D point cloud dimensions (mm)	Vernier calipers (mm)	Tape measure (mm)	Deviation (mm)
1	Vase with decorative cloud pattern Length	342.35	–	342	0.35
2	Diameter of the middle of the vase	87.83	86.66	–	1.17
3	Handrail to waistline spacing	166.5	165.28	–	1.22
4	Handrail height	688.46	–	687	1.46
5	Height of lower part of column	750.04	–	749	1.04
6	Height of upper column	304.22	–	305	0.78
7	Diameter of the upper column	157.68	156.49	–	1.19
8	Side length of the lower column	160.95	159.14	–	1.81
9	Handrail thickness	79.8	80.05	–	0.25
10	Handrail length	1473.82	–	1475	1.18

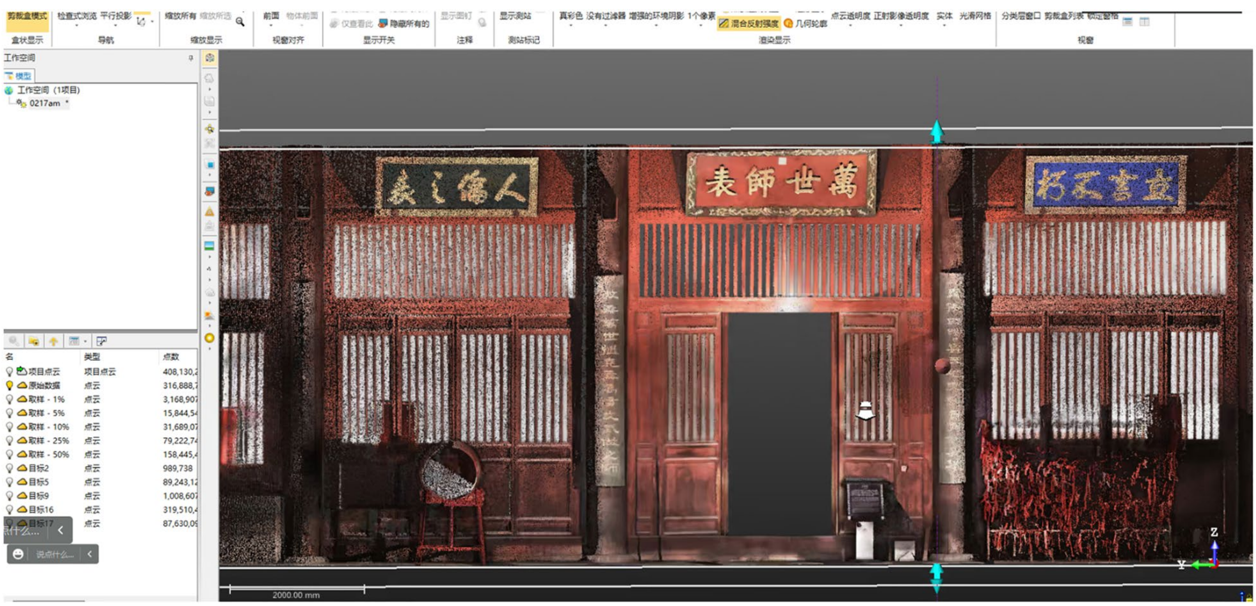

Fig. 14 Pre-thinning

and was no more than the 1 m height of the stone. Therefore, the stone decorative element had high point cloud model accuracy.

Point cloud data noise

During point cloud data processing, noise was actively removed from the point cloud model and the point clouds underwent dilution. Specifically, 316,888,773 point clouds were diluted by 50%, 25%, and 10%, and subsequently had 158,445,426, 79,222,742, and 31,689,077 points, respectively. Considering the human factor in the measurement point selection facilitated the conclusion that scanned data optimisation by thinning was negligible. The pre- and post-thinning processes are depicted in Figs. 14 and 15, respectively.

Point cloud data stratification

The observation approach yielded results in a point cloud model without layering, radiation, divergence, and conicality (see Fig. 16). The abovementioned quality control methods achieved better quality control of the basic model of cultural relics. The production of an accurate heritage building model synchronised scientific data and cultural heritage in the heritage conservation field, which

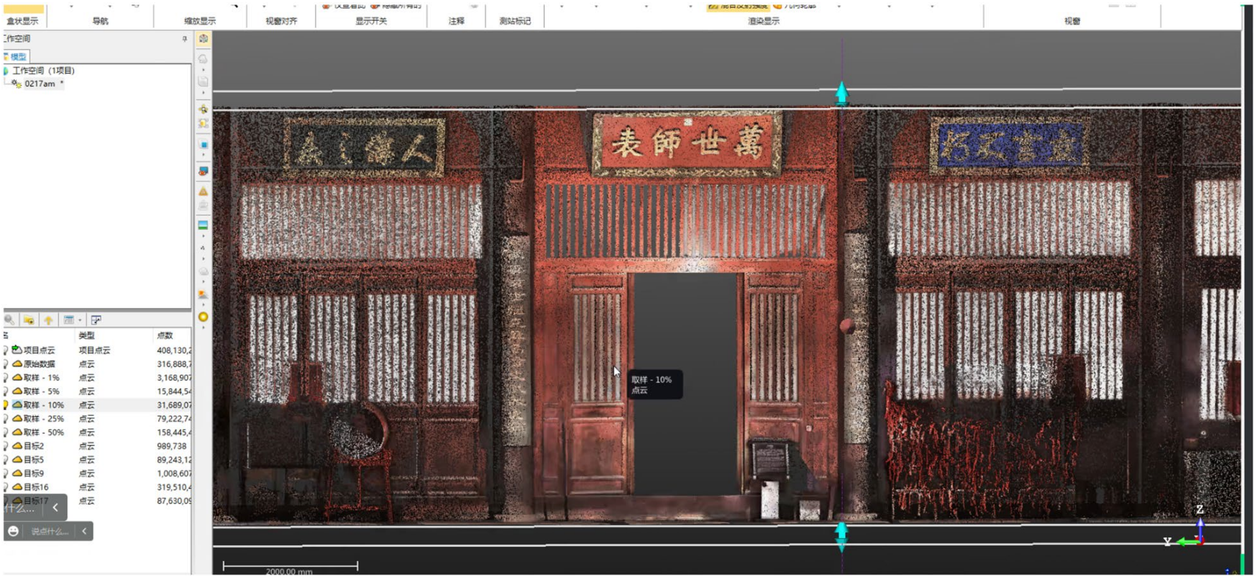

Fig. 15 After thinning

significantly enhanced the ability to obtain accurate data on heritage buildings.

Conclusion

The findings demonstrated the importance and necessity of maintaining historic structures linked to cultural artifacts and cataloguing their architectural layouts. The benefits of 3D laser scanning, such as contactless operation, speed, and high precision, are well-known, specifically in accurately mapping and modelling historic architectural remnants. The accurate mapping of historic structures using 3D laser scanning technology accomplishes two goals simultaneously: (i) preserving the most accurate, thorough, and original records of cultural treasures while also, (ii) yielding vital information for conservation and repair. Subsequently, the accurate information facilitates the saving, restoration, or rebuilding of historic structures and funding of associated projects.

This investigation presented a case study that focused on the Great Achievement Palace in the historic city of Yuci, Jinzhong City, Shanxi Province. The study presented thorough explanations of the technical steps involved in 3D scanning, data-processing techniques, and model outcome fine-tuning for error analysis. Accuracy analysis revealed the key factors to consider before the measurement stage. It was crucial to choose a high-precision 3D scanning tool and establish the scanning locations in accordance with the specifications. Furthermore, it was essential to maintain a constant repetition rate during model scanning. Moreover, scanning the decorative elements of the structure required additional care as it involved more sites and higher overlap rates. The elements of field of view settings and image resolution should also be considered. Additionally, the effects of point cloud noise, thinning, and stitching on model accuracy should be considered throughout the data processing stage.

Currently, 3D point cloud models are recognised as a powerful tool for recording information on heritage architectural features and data. The installation of

Fig. 16 Point cloud model of the decoration of the pillar head of the Great Achievement Palace

high-precision model data is significantly important to protect heritage buildings.

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