Digital Mapping and Tilt Analysis of Ancient Towers based on the Integration of Oblique Photography and 3D Laser Scanning Technology

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Abstract: As an important historical and cultural heritage in China, the digital protection and structural health monitoring of ancient pagodas are key measures for the inheritance of cultural heritage. Aiming at the problems of low efficiency, insufficient accuracy, and difficulty in obtaining comprehensive internal and external structural information of buildings with traditional ancient pagoda surveying and mapping methods, this paper adopts the combination of tilt photography and 3D laser scanning technology to conduct omnidirectional digital surveying and mapping of an ancient pagoda under a unified datum. Through field data collection, in-house data processing and fusion, a 3D real-scene model and a high-precision point cloud model of the ancient pagoda were constructed, and floor plans, elevations and sections of each floor were extracted and generated. Based on the digital model, the inclination state of the ancient pagoda was accurately analyzed, and the measurement results were verified against relevant historical documents, confirming their accuracy and reliability. Research shows that the fusion technology of tilt photography and 3D laser scanning can realize efficient and high-precision collection and digital reconstruction of internal and external structural information of ancient pagodas, provide scientific and comprehensive digital data support for the protection, restoration, structural monitoring and historical and cultural research of ancient pagodas, and also provide feasible technical solutions for digital surveying and mapping of similar ancient buildings.

Keywords: Ancient Pagoda; Tilt Photography; 3D Laser Scanning; Digital Mapping; Inclination Analysis; Cultural Heritage Protection

1. Introduction

The ancient pagoda is a treasure of ancient architectural art in China. It carries a wealth of historical, cultural and scientific values, and is an important physical carrier for the study of ancient architectural crafts, religious culture and social development. However, due to natural erosion, geological changes and human factors, many ancient pagodas suffer from inclination, weathering, deterioration and other damages, and their structural safety and integrity have been seriously threatened. Carrying out accurate mapping and health monitoring of ancient pagodas has become an urgent need for cultural heritage protection [1].

Traditional ancient pagoda surveying and mapping mainly rely on artificial total station surveying, manual drawing and other methods. There are disadvantages such as low operational efficiency and high labor intensity, and limited measurement range. It is difficult to comprehensively capture the complex three-dimensional structure and detailed characteristics of ancient pagodas, and it may cause potential damage to the ancient pagoda body, which cannot meet the needs of modern digital protection [2]. With the rapid development of surveying and mapping technology, tilt photography and 3D laser scanning technology have been gradually applied to the digital field of ancient buildings [3], both of which have advantages [4]. Tilt photography technology can quickly obtain high-resolution texture information and real-life three-dimensional models of the target object through drone aerial photography, and visually restore the appearance of the building; three-dimensional laser scanning technology has the characteristics of non-contact, high precision and high efficiency, which can accurately obtain three-dimensional spatial coordinate information of the interior and exterior surfaces of the building, and make up for the data acquisition blind areas of tilt photography in hidden areas (such as the interior of the ancient pagoda and under the roof) [5].

At present, when a single surveying and mapping technology is applied to ancient pagoda surveying and mapping, it is difficult to balance the integrity, accuracy and intuition of data [6]. Therefore, this paper uses tilt photography and three-dimensional laser scanning fusion technology to carry out all-round digital surveying and mapping of an ancient pagoda under a unified measurement benchmark, builds a complete digital model of the ancient pagoda through multi-source data fusion, extracts two-dimensional drawings of the building, and carries out inclination analysis and historical data verification. The purpose is to provide accurate and comprehensive technical support for digital protection, structural monitoring and follow-up research of ancient pagodas, and promote the innovation and application of digital protection technology of ancient buildings.

2. Overview of the Study Area and Research Methods

2.1 Overview of the Study Area

The object of this study is a historical ancient pagoda (hereinafter referred to as "Research Ancient Pagoda"), which was built in the Song Dynasty and is an octagonal seven-story pavilion-style brick pagoda with a height of about 39 meters and a length of about 4.5 meters on each side of the ground floor. The pagoda body has one room on each side. On the north side of the ground floor, there are arched doors, and on the east, south, and west sides are false arched doors; on the second to sixth floors, there are two arched doors, two opposite sides, and the up and down positions are wrong; on the top floor, there are four doors on the east, south, west, and north sides. The eaves overlap between layers, with the bricks hiding the corner pillars, the forehead, the bucket and the diamond teeth, and the elliptical phase wheel and the iron brake, which have the architectural style of the Song Dynasty. After hundreds of years of wind and rain erosion, the ancient pagoda has experienced surface erosion, efflorescence and salt attack in some areas, and the pagoda has a large inclination. The pagoda inclines by approximately 4° to the northwest. The spire deviates from the vertical line by about 2.6 meters and is known as the "Leaning Pagoda of Pisa of the East". It is urgent to carry out accurate mapping and structural state analysis to provide data support for protection and repair work. The status of the Ancient Pagoda is shown in Figure 1.

Figure 1. Current State of the Ancient Pagoda

The surrounding terrain of the research object is relatively flat, and there is no tall barrier, which is convenient for drone tilt photography and ground 3D laser scanning operations. At the same time, the research area has convenient transportation, which can ensure the smooth entry of surveying and mapping equipment and personnel, and provide good basic conditions for data collection in the field.

2.2 Research Methods and Technical Routes

This study takes "Data Acquisition — Data Processing — Model Construction — Achievement Extraction — Inclination Analysis — Verification and Application" as the core technical route, integrates tilt photography and 3D laser scanning technology to achieve all-round digital mapping and inclination analysis of ancient pagodas. The specific technical process is as follows:

(1) Preparations: Collect and study the historical documents of the ancient pagoda, past surveying and mapping data and surrounding terrain data,

clarify the surveying and mapping scope and accuracy requirements; carry out on-site surveys, investigate potential operational hazards, plan drone flight routes and three-dimensional laser scanning and measuring stations; unify the measurement benchmarks, and adopt the national 2000 geodetic coordinate system as the plane benchmark, and the national 2000 geodetic coordinate system as the elevation benchmark to ensure that the data collected by the two technologies can be fused and matched under the same benchmark.

(2) Field data acquisition: The UAV tilt photography technology is used to collect the appearance texture and spatial information of the ancient pagoda to obtain high-resolution tilt images; the 3D laser scanning technology is used to arrange multiple stations to scan the inner and outer surfaces of the ancient pagoda in all directions to obtain high-precision three-dimensional point cloud data. The tilt image control point and 3D scanning control target layout are shown in Figure 2.

Figure 2. Distribution of Image Control Points and 3D Scanning Targets for Oblique Photogrammetry

(3) In-house data processing: The tilt image is subjected to air three encryption, dense matching, etc., to build a three-dimensional model of the ancient pagoda scene; the three-dimensional point cloud data is spliced, denoised, coordinate conversion, etc., to obtain a high-precision ancient pagoda point cloud model; based on a unified benchmark, the feature point matching and ICP algorithms are used to achieve data fusion of the two models to improve the integrity and accuracy of the model [7].

(4) Achievement Extraction: Based on the fused digital model, professional surveying and mapping software is used to extract the plan, elevation and sectional drawings of each floor of the ancient pagoda to ensure that the drawing data is consistent with the actual building and meet the needs of protection, repair and design.

(5) Inclination analysis: Based on the high-precision point cloud model and the three-dimensional model of the real scene, select the key feature points of the ancient pagoda, calculate the inclination direction, angle and displacement of the pagoda body, and analyze the reasons for the inclination.

(6) Verification and Application: Compare the inclination analysis results with the historical documents and past surveying and mapping records of the ancient pagoda to verify the accuracy of the measurement results; based on the digital results, provide technical suggestions for the protection and repair of the ancient pagoda and structural monitoring.

3. Field Data Collection and In-house Data Processing

3.1 Field Data Collection

3.1.1 Oblique Photographic Data Acquisition

This tilt photography data acquisition uses a DJI M4E drone with 20 million effective pixels and an equivalent focal length of 24mm. Combined with the study of the height and shape of the ancient pagoda, the drone flight parameters are planned: 1) The courtyard area where the pagoda is located is photographed by inclined sweeping, the flight height is 80 meters, the forward overlap≥85%, and the side overlap≥ 80%, to ensure the continuity and integrity of the image data; 2) For the detail areas such as the eaves and corners of the ancient pagoda, manual circular flight is adopted and different The method of tilt shooting under altitude improves the accuracy of the model [8]. The average circumference radius is 7 meters, the forward overlap ≥ 90%, and the lateral overlap≥ 85%; 3) The basic control is established by satellite positioning control measurement in the study area, and 4 image control points are evenly arranged to accurately collect the national 2000 coordinates of the image control point. The accuracy of the image control point≤2cm, providing accuracy guarantees for subsequent air three encryption and model construction to provide a basis for coordinate registration between different types of data.

During the acquisition process, strictly control the flight attitude to avoid image blur or position deviation due to airflow interference; synchronously record flight logs, including flight time, flight altitude, weather conditions and other information to ensure data traceability. A total of 927 tilted images were collected this time, and 119 images were manually close to the flight. The image quality was good, and there were no obvious blurring, overexposure or insufficient problems, etc., to meet the subsequent data processing needs.

3.1.2 3D Laser Scanning Data Acquisition

The 3D laser scanning data acquisition adopts the Leica P40 ground 3D laser scanner, the scanning accuracy is 8 ", the ranging accuracy is 1.2mm+10ppm, the scanning rate is up to 1,000,000 points/second, the range noise is 0.5 mm @ 50 m, the precision dual-axis compensation technology, the accuracy is up to 1.5", and the scanning distance is up to 270m. According to the structural characteristics and surveying and mapping needs of the ancient pagoda, a multi-station scanning method is adopted to rationally arrange surveying stations around and inside the ancient pagoda. The overlap rate of adjacent surveying stations is ≥ 30%, ensuring that there are no scanning blind spots. For hidden areas such as stairs and corridors inside the ancient pagoda, the scanner angle is adjusted to conduct targeted scanning to comprehensively capture internal structural information.

Before scanning, the scanner is calibrated to ensure the accuracy of the equipment; 3 control targets are placed around the study object, and the total station is used to accurately obtain the national 2000 coordinates of the control target. At the beginning of scanning, control targets and temporary targets near the measuring station are first scanned, and then global scans are performed; the connection pattern between the measuring station and the measuring station is formed by 3 or more common targets, and finally the complete route of connect and close to control targets is formed. The point cloud density of the global scan is set to 2cmm @ 10m; during the scanning process, the scanning data is monitored in real time to ensure that the scanning data is complete and runs without abnormalities. A total of 40 stations were set up this time, and 275 million points cloud data were collected. The data density of the point cloud is uniform, which can clearly reflect the detailed characteristics of the inner and outer surfaces of the ancient pagoda.

3.2 In-house Data Processing

3.2.1 Tilt Photography Data Processing

DJI Terra software is used to process tilted images in the industry. The main processes include: image preprocessing, empty triple encryption, dense matching, and three-dimensional modeling. First, the collected inclined images are screened, the blurred and distorted images are removed, and the remaining images are color balanced to ensure that the image tone is consistent; then, the image control point coordinates are imported, the aero triangulation processing is carried out, and the external orientation elements of each image are obtained through automatic matching of feature points and adjustment calculation to build a three-dimensional empty three-dimensional model; then, based on the empty three-dimensional model, a high-density point cloud is generated, and then a three-dimensional model of the Ancient Pagoda scene is generated through triangulation modeling and texture mapping, as shown in Figure 3. The texture of the model is clear, the shape is realistic, and it can intuitively reflect the appearance characteristics and details of the ancient pagoda.

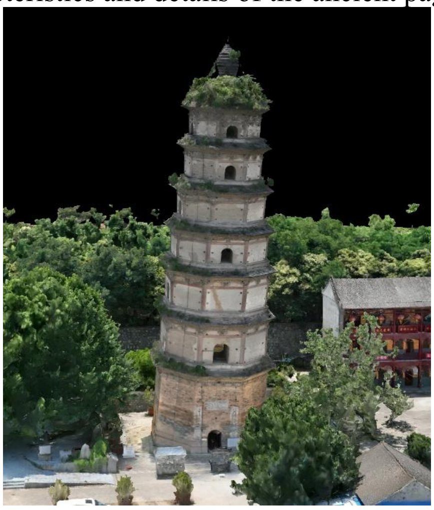

Figure 3. Real Scene 3D Model of the Ancient Pagoda

3.2.2 3D laser scanning data processing

The 3D laser scanning point cloud data is processed by Leica Cyclone software. The main processes include: station splicing, point cloud denoising, coordinate conversion, and point cloud down sampling. First, based on the target coordinates, the iterative closest point (ICP) algorithm is used for station stitching to ensure that the cloud data of each station is under the same coordinate system; then, the statistical filtering method is used to remove the noise points and outliers in the point cloud data, manually remove the unrelated object point clouds, and retain the effective point clouds; then, the point cloud data after stitching and denoising is converted into a unified measurement benchmark, which is consistent with the oblique photographic model coordinate system; finally, the point cloud data is streamlined, the amount of data is reduced without affecting the accuracy, and the efficiency of subsequent model fusion and achievement extraction is improved to obtain a high-precision ancient pagoda point cloud model. As shown in Figure 4. The point cloud model can accurately reflect the three-dimensional spatial coordinate information of the inner and outer surfaces of the ancient pagoda.

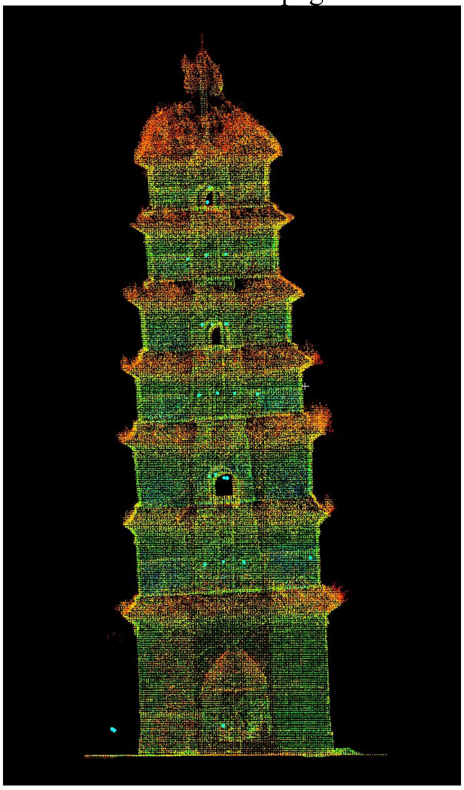

Figure 4. 3D Laser Scanning Point Cloud Data of the Ancient Pagoda

3.2.3 Multi-Source Data Fusion

In order to achieve the complementary advantages of the tilt photography model and the 3D laser scanning point cloud model, and improve the integrity and accuracy of the digital results, the feature point matching and ICP algorithms are used for multi-source data fusion [9]. First, according to the unified coordinate system, the two model data can be initially registered together, and then the common feature points (such as the corners of the ancient pagoda, the edges of doors and windows, etc.) are extracted from the two models for preliminary rough registration; then, the registration accuracy is optimized based on the ICP algorithm to ensure that the registration error is ≤ 2cm; finally, the point cloud data and the real scene three-dimensional model are fused to generate a fusion model that combines high-precision geometric information and high-realistic texture information, which not only retains the texture advantages of the tilt photography model, but also combines the accuracy advantages of the three-dimensional laser scanning model to achieve comprehensive coverage of the structural information inside and outside the ancient pagoda [10].

4 Digital Achievement Extraction and Inclination Analysis

4.1 Digital Achievement Extraction

Based on the fused digital model (real scene three-dimensional model and point cloud model), Autodesk ReCap and Autodesk AutoCAD are used to extract the two-dimensional mapping results and three-dimensional results of the ancient pagoda, including:

(1) Real 3D model: The texture resolution is 1.185cm/px, which can clearly show the appearance, decorative details and surrounding environment of the ancient pagoda. It supports 360° panoramic browsing, distance measurement, area measurement and other functions to facilitate the visual display and follow-up research of the ancient pagoda.

(2) Point cloud model: The point spacing is 2mm, and the coordinate accuracy is 3.6mm, which can accurately reflect the three-dimensional space shape of the inner and outer surfaces of the ancient pagoda, providing high-precision data support for structural analysis and disease detection.

(3) Two-dimensional drawings: extract the floor plans, elevation drawings, and cross-sectional drawings of each floor of the ancient pagoda, with a scale of 1:200, drawn in strict accordance with architectural drawing specifications, and marked with key dimensions, structural details, and elevation information. Among them, the plan clearly shows the plan layout of each layer, the position and size of doors and windows; the elevation map shows the front, side morphology and height changes of the ancient pagoda; the cross-sectional map shows the internal structure of the ancient pagoda, the thickness of each layer and the elevation relationship. The digital results of the planes, facades and profiles of the ancient

pagodas are shown in Figure 5, and the accuracy of the drawings meets the needs of protection and repair design and construction.

All digital results are checked for accuracy. Through field sampling measurements and model comparison, the results meet the requirements of the "Code for Surveying and Mapping of Ancient Buildings" [11]. The error in the plane position is ≤ 15mm, and the error in the elevation is ≤ 18mm, which meets the accuracy requirements of digital protection and structural monitoring.

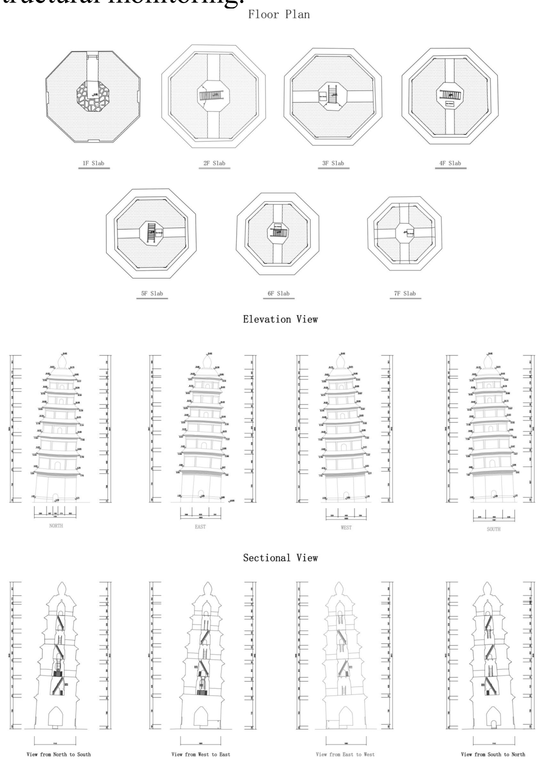

Figure 5. Digitized Drawing Results (Planes, Facades, Sections)

All digital results are checked for accuracy. Through field sampling measurements and model comparison, the results meet the requirements of the "Code for Surveying and Mapping of Ancient Buildings" [11]. The error in the plane position is ≤ 15mm, and the error in the elevation is ≤ 18mm, which meets the accuracy requirements of digital protection and structural monitoring.

4.2 Ancient Pagoda Inclination Analysis

4.2.1 Inclination analysis method

Based on the high-precision point cloud model, the characteristic point analysis method was used to carry out the ancient pagoda inclination analysis. Select the key feature points at the bottom, middle, and top of the ancient pagoda (such as the corners of the pagoda body, the end points of the central axis, etc.), extract the three-dimensional coordinates of each feature point, take the plane where the feature point at the bottom of the ancient pagoda is located as the datum plane, calculate the offset of the top feature point from the datum plane, and then determine the inclination direction, inclination angle, and inclination of the ancient pagoda; at the same time, combining with the three-dimensional model of the real scene, visually observe the inclination shape of the ancient pagoda, analyze the inclination distribution characteristics, and exclude the impact of measurement errors on the analysis results.

The inclination angle is calculated using the following formula:

$$\tan\alpha = \frac{\Delta l}{H} \quad (1)$$

where is the inclination angle of the ancient pagoda, Δl is the horizontal offset (m) of the top center relative to the bottom center, and H is the height (m) of the top center relative to the bottom center.

4.2.2 Inclination Analysis Results

Through the coordinate analysis and calculation of the key feature points of the ancient pagoda, the inclination analysis results of the ancient pagoda in this study are as follows:

(1) Inclination direction: The overall offset of the ancient pagoda is from the southeast to the northwest, the inclination direction is stable, and there is no obvious irregular inclination.

(2) Inclination angle: Taking the ground center of each layer of the ancient pagoda as the reference point, the offset, offset direction and offset angle of each layer are shown in Table 1 below. The offset angle of each layer of the pagoda body is about 4°, there is no abnormal offset, and there is no irregular inclination phenomenon.

Table 1 Ancient Pagoda Inclination Analysis Table

Item	Offset (m)	Rotation	Offset azimuth (°)
1st Floor Ground Center - 2nd Floor Ground Center	0.41	3.92	Northwest 44.93
2nd Floor Ground Center - 3rd Floor Ground Center	0.37	4.37	Northwest 47.74
Level 3 Ground Center - Level 4 Ground Center	0.34	4.20	Northwest 45.19
4th Floor Ground Center - 5th Floor Ground Center	0.32	4.36	Northwest 44.04

5th Floor Ground Center - 6th Floor Ground Center	0.26	3.84	northwest 46.54
6th Floor Ground Center - 7th Floor Ground Center	0.27	4.15	Northwest 47.78
7th Floor Ground Center - 7th Floor Top Center	0.22	3.46	Northwest 32.83
7th Floor Top Center - Spire	0.46	3.49	Northwest 39.32
Level 1 Ground Center - Spire	2.65	3.93	Northwest 43.73

(3) Inclination: The horizontal offset of the tip of the ancient pagoda relative to the center of the bottom is 2648.2mm. Looking at the relevant monitoring data, the horizontal offset of the Ancient Pagoda has changed very little over the years, indicating that it is basically in a steady state of inclination.

Combined with the analysis of the point cloud model and the three-dimensional model of the real scene, the inclination of the ancient pagoda is mainly due to natural factors (such as long-term wind and rain erosion, foundation settlement), and the influence of human factors is small. Although the current inclination is stable, the horizontal offset is large, and it still needs to be regularly monitored and paid attention to to to prevent the sudden increase in inclination. At the same time, the local surface erosion of the pagoda body, crisp alkali and salt flooding have also had a certain impact on the health status, which needs to be paid attention to in the follow-up protection and repair.

5 Results Validation and Discussion

5.1 Results Validation

In order to verify the accuracy of the results of this digital surveying and inclination analysis, the survey results were compared with the historical literature and previous survey records of the research pagoda. The specific verification contents are as follows:

(1) Dimension comparison: The key dimensions of each layer of the ancient pagoda extracted this time (such as pagoda body diameter, layer height, door and window dimensions, etc.) were compared with historical literature records and previous survey drawings, and the errors were all within 2cm; compared with the measured dimensions of the field steel ruler, the errors were all within 1cm; the accuracy requirements were met, which confirmed the accuracy of the digital results.

(2) Inclination comparison: Comparing the inclination angle and inclination direction of the ancient pagoda calculated in this calculation with the inclination data in the historical record, the results show that the inclination direction of the ancient pagoda is the same, and the inclination angle is close to 4°, which is within a reasonable range, indicating that the inclination analysis results are true and reliable, and can accurately reflect the current inclination state of the ancient pagoda.

(3) Structure Comparison: Through the comparison of the three-dimensional model of the actual scene and the structural characteristics of the ancient pagoda recorded in the historical documents, the model can completely restore the architectural style, decorative details and internal structure of the ancient pagoda, which is highly consistent with the historical description, indicating that this digital model can accurately capture the overall shape and detailed characteristics of the ancient pagoda, providing a precise digital carrier for historical and cultural research.

5.2 Discussion

This study uses tilt photography and three-dimensional laser scanning fusion technology to realize the all-round digital surveying and inclination analysis of ancient pagodas. Compared with traditional surveying and mapping methods, it has the following advantages: First, it uses a non-contact measurement to avoid damage to the ancient pagoda body and ensure the safety of cultural heritage; second, it has high operation efficiency. Compared with manual surveying and mapping, it greatly shortens fieldwork and in-house processing time. Setting and in-house data processing time, reducing labor intensity; third, high data accuracy, combining the advantages of two technologies, to achieve high-precision collection of structural information inside and outside the ancient pagoda, digital results can meet the needs of protection, repair, structural monitoring; fourth, rich results, not only including traditional two-dimensional drawings, but also built a real scene three-dimensional model and point cloud model, for the digital display of the ancient pagoda, historical research provides diversification carrier.

At the same time, this study also has certain shortcomings: First, under complex weather conditions (such as strong winds and heavy rain), drone tilt photography and 3D laser scanning operations will be affected, which may lead to a decrease in data acquisition accuracy; second, there is still room for improvement in scanning accuracy in some hidden areas inside the pagoda (e.g., narrow corridors and the spire interior). Subsequently, small handheld laser scanners can be used for supplementary scanning to further improve the digital model; third, this inclination analysis is mainly based on current measurement data, and no long-term monitoring was performed. Subsequently, a long-term monitoring system for the ancient pagoda inclination can be established to track inclination changes in real time, providing dynamic data support for protection and repair work [12].

In view of the above shortcomings, the future can be optimized from three aspects: first, optimize the operation plan, rationally plan the operation time, avoid bad weather, and improve the accuracy of data collection; second, introduce miniaturized and high-precision surveying and mapping equipment, supplement the data collection in hidden areas, and improve the digital model; third, establish a digital monitoring platform for ancient pagodas, integrate multi-phase surveying and mapping data, achieve dynamic monitoring and early warning of the inclination state, and promote the development of the protection of ancient pagodas in the direction of intelligence and refinement.

6. Conclusion

Taking an ancient pagoda as the research object, this paper uses tilt photography and three-dimensional laser scanning fusion technology to carry out all-round digital surveying and mapping under a unified benchmark. Through external data collection, internal data processing and fusion, the three-dimensional model of the ancient pagoda scene and the high-precision point cloud model have been successfully constructed, and the digital results such as the plan diagram, elevation diagram, and section diagram have been extracted and generated. Based on the digital model, the inclination analysis has been carried out to clarify the inclination direction, inclination angle, and inclination amount of the ancient pagoda. Combined with the comparison and verification of historical literature, the accuracy and reliability of the measurement results have been confirmed.

The research shows that tilt photography and 3D laser scanning fusion technology can effectively make up for the shortcomings of single surveying and mapping technology, achieve efficient and high-precision collection and digital reconstruction of structural information inside and outside the ancient pagoda, and provide scientific and comprehensive digital data support for the protection and repair of ancient pagodas, structural monitoring and historical and cultural research. The technical scheme has the advantages of simple operation, high efficiency, high precision and non-contact, etc., and can be widely used in the digital surveying and mapping and protection of similar ancient buildings. It has important practical significance and application value to promote the development of the digital protection of historical and cultural heritage in China.

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