Research on the Integrated Application of Multi-scale 3D Digital Technologies in Village Heritage Conservation

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Abstract

Traditional village heritage encompasses multi-scale complexities, ranging from macro-level landscapes to micro-scale architectural details, which traditional survey methods often fail to capture adequately. This study constructs an "Air-Ground Coordination" framework that combines UAV oblique photogrammetry, UAV LiDAR, micro-UAVs, and both handheld and metrology-grade 3D laser scanning. By analyzing five digital surveying techniques through practical case studies, the research demonstrates the strengths and integration of multi-source methods for diverse village settings. The proposed "dynamic hierarchical collection, multi-device collaborative operation, and cross-scale integration" digital documentation system advances heritage conservation from static records to systematic, multi-layered digital twin management, offering a potential approach for future preservation efforts.

1. Introduction

Village heritage, as a comprehensive carrier of cultural landscapes, encompasses not only tangible buildings, settlements, and landscape elements but also embodies the social structure, ecological construction wisdom, and production–living modes of specific regions. It is characterized by cross-scale and multi-level complexity, which dictates that its conservation and rehabilitation require comprehensive and multidimensional documentation, ranging from the macro-scale settlement landscape patterns and environmental context to the mesoscale architectural forms and spatial structures down to the micro-scale construction techniques, details, and physical deterioration. Traditional surveying methods are relatively inefficient and limited in terms of information dimensions, making it challenging to capture complex features accurately and thus failing to meet the demands of heritage conservation work (Qiao, 2025).

In recent years, the development of digital technology has brought new opportunities for heritage documentation and conservation. Technologies such as photogrammetry and Three-dimensional (3D) laser scanning can quickly and efficiently obtain high-precision 3D spatial data and high-definition texture information in a non-contact manner, providing a data foundation for heritage digital archiving, value assessment, rehabilitation design, monitoring, and early warning (Wu et al, 2022). Singular digital technologies also face limitations in addressing multi-scale requirements to comprehensively and efficiently collect multi-layered information (Jiao, 2022). For example, unmanned aerial vehicle (UAV) oblique photogrammetry is highly automated and relatively cost-effective, capable of quickly capturing multi-angle images of targets and reconstructing 3D reality models. However, its aerial perspective is limited, generally making it difficult to capture information on the undersides of structures and in areas that are occluded (Wang, 2022; Huang, 2024). Terrestrial laser scanners (TLS) can acquire high-precision, dense point cloud information from target surfaces but are unable to obtain data from rooftops and other high areas and are costly—typically used only for key cultural relics—making it challenging to implement across the numerous village heritage sites widely. Therefore, it is necessary to integrate aerial and land surveying methods and combine multi-source data obtained through hierarchical and multi-scale approaches to enhance the completeness and accuracy of surveying results, thereby providing comprehensive data support for the conservation and research of village heritage (Yang, 2018.).

This study examines the integration of multiple 3D digital surveying technologies to establish an 'Air-ground Coordination' cross-scale digital documentation framework for the digitization and conservation of village heritage, spanning from macro to micro scales. The study will discuss multi-source 3D digitization methods, including UAV oblique photography, UAV Light Detection and Ranging (LiDAR) scanning, handheld laser scanning, and high-precision laser scanning, to explore application strategies, technical advantages, and limitations in documenting the characteristics of village heritage at different scales. Based on this, this paper proposes a technical framework, aiming to provide a systematic, fine-grained, and dynamic digital solution for village heritage conservation, and to promote the transformation in heritage conservation from static, single-object documentation towards the construction of a systematic, dynamically managed digital twins.

2. Multi-Scale Characteristics of Village Heritage and Surveying Needs

The complexity of village heritage across multiple scales can be summarised into three spatial levels: macro, meso, and micro. These levels have distinct heritage characteristics and values, and they require varying documentation requirements for data. At the mesoscale, the core lies in the regional settlement landscape pattern, the clustering relationships between settlements, the landscape ecological structure of settlements and natural environments, and the collaborative interplay between production and lifestyle patterns. Therefore, the considerations extend beyond the settlement groups to include the natural elements surrounding them, such as farmland, water systems, mountains, and forests, as well as the transportation network connecting each functional area. At this scale, heritage value is manifested more in the overall human–land relationship. Therefore, digital documentation should emphasize how to present the integrated landscape of settlements and environments, as well as how to obtain large-scale, accurate geographic spatial data efficiently. The digitally recorded data provides a basis for subsequent quantitative research, such as geographic information analysis and ecological analysis, thus helping to elucidate the historical context of village site selection, land use patterns, and regional coordinated development.

The mesoscale is an important intermediate level that connects the macro-scale settlement landscape patterns with the micro-scale characteristics of individual buildings. It focuses on the spatial layout and structure of a single settlement or building complex, including its boundaries, spatial patterns, street network, and the form and distribution of public spaces. In addition, the detailed land use pattern, the overall condition of building roofs, and vegetation coverage are also important objects of study at this scale. Therefore, the challenge with digital documenting at the mesoscale is how to maintain data completeness while providing sufficient precision to support the analysis of settlement morphology. For example, precise data on building contours and street widths can be utilized for typological and morphological studies. Information on building facades, roofs, and other deteriorated features can be used to make preliminary assessments of the overall preservation status of building groups.

The micro-scale focuses on the detailed characteristics and status of the basic units that constitute the village—individual buildings and spatial places, including structural systems, building materials, craftsmanship, floor plans, and spatial usage patterns. It also includes more detailed decorative elements, carved motifs, material textures, and information on damage and deterioration. For traditional village heritage, the micro level provides richer historical information and is crucial to interpreting heritage value. Therefore, the core issue is how to obtain higher-precision models to authentically and comprehensively capture the historical information of the heritage, thereby better supporting subsequent detailed restoration design, deterioration analysis, digital exhibition, and other related tasks.

Based on the above macro-, meso-, and micro-level spatial features and requirements, the study proposes five technical methods and conducts practical implementation studies on selected cases, analysing the workflow, technical limitations, and application scenarios for the integrated application of different technologies. These include small UAVs equipped with five-lens cameras for photogrammetry at the macro scale, oblique photogrammetry with a small UAV equipped with a five-lens camera at the meso scale, LiDAR-based point cloud scanning from UAVs, oblique photogrammetry using micro-UAVs meso scale, and handheld 3D laser scanning, metrology-grade 3D laser scanning at the micro-scale.

3. Multi-scale Digital Technology Methods and Applications

3.1 Macro-scale: Oblique Photogrammetry with a Small UAV and Five-Lens Camera

For macro-scale data acquisition needs, a small UAV equipped with a five-lens oblique photogrammetry system can effectively capture large-area, multi-angle, high-overlap imagery. The five-lens camera retains the traditional vertical aerial photograph while adding four tilted lenses for forward, rearward left, and right views. Using a simultaneous exposure method with all four lenses, a single flight can capture one vertical image and four tilted images from different angles synchronously, thereby obtaining more detailed terrain and object information (Figure 1). This multi-view data collection approach enriches the amount of ground information collected. It overcomes the issue of missing information on building facades and sides of tall objects in traditional orthophotos. It can quickly generate realistic models that combine authentic textures with 3D structures and has high-efficiency coverage capabilities in shortening the data collection cycle for large areas.

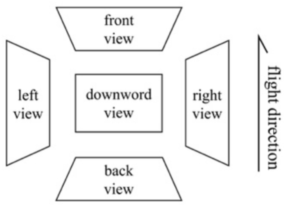

Figure 1. Relative lens positions in a five-lens oblique configuration

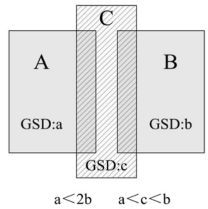

Figure 2. Diagram of flight zones and transition zones with different GSD

For certain large-scale village landscapes or archaeological sites, the surveying process faces challenges such as vast operation areas, complex working environments, and limitations in equipment performance and battery capacity. Therefore, it is usually necessary to divide the whole area into several zones to plan multiple flight routes. To facilitate the final construction of a photogrammetric model, sufficient overlap between different mission areas must be maintained—typically around 80% forward overlap and over 70% side overlap. On the other hand, data accuracy requirements may vary for different zones within the same large site. This case employs a gradient resolution strategy for flight zones and route planning, utilizing low-altitude, high-resolution flights for central areas and conducting higher-altitude, lower-resolution flights for peripheral or secondary areas. A transition flight zone is established between them to ensure that the resolution difference does not exceed twice. This optimizes the data volume and processing efficiency while ensuring the accuracy of key information (Figure 2).

The first case is in Jiaolewei, Wencun Town, Taishan City, Guangdong Province. The total area is approximately 12 km², including 108 natural villages. Each settlement is small in scale and tightly interwoven with productive landscapes such as fields, fishponds, and water networks scattered across an open, coastal tidal flat that was reclaimed starting in the late Qing Dynasty. To comprehensively document the unique landscape pattern, the study utilizes a DJI Matrice 350 RTK (Shenzhen DJI Innovation Technology Co., Ltd., Shenzhen, China) drone equipped with a SHARE 203S PRO for oblique photogrammetry. The SHARE 203S PRO is a high-performance five-lens oblique camera system, boasting a total of approximately 225 million effective pixels across five full-frame sensors and weighing around 830g without its gimbal. The DJI Matrice 350 RTK is a small four-rotor UAV that boasts long endurance, high payload capacity, and RTK/PPK high-precision positioning, offering a stable flight platform for large-area, high-precision surveying with its five-lens camera.

Before aerial surveying, based on the village boundaries and preliminary investigations, the entire area was divided into 25 flight zones (Figure 3). Flight zones A to N covered the core settlement landscape cluster, with a Ground Sample Distance (GSD) of 120 cm/pixel; flight zones O to U were adjacent to the edge of the Jiaolaiwei area and were of lower importance, with a GSD of 280 cm/pixel; four additional flight zones were designated as transition zones, with a GSD of 200 cm/pixel. The entire survey took 4 days to complete, with a total of 40,235 images acquired. The data was processed using DJI Terra to create a visible light model covering the entire area. This model visually illustrates the landscape characteristics of the interconnected 'settlement, land, pond, and water' in the reclamation context, providing a comprehensive data foundation for subsequent GIS spatial analysis and historical transformation research (figure 4).

However, the model also highlighted inherent issues of oblique photogrammetry, such as voids over water surfaces and the omission of fine texture details. Furthermore, when forward overlap is controlled at 80% and side overlap at 70–80%, the resulting image coverage often presents a dense state in the central region but a weak state at the edges, meaning that the accuracy of the aerial photography edge area model is slightly lower than that of the centre area.

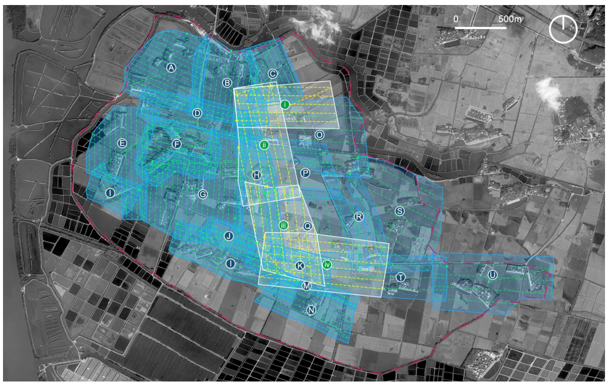

Figure 3. Flight zone and route planning with different GSD in the Jiaole Wei case

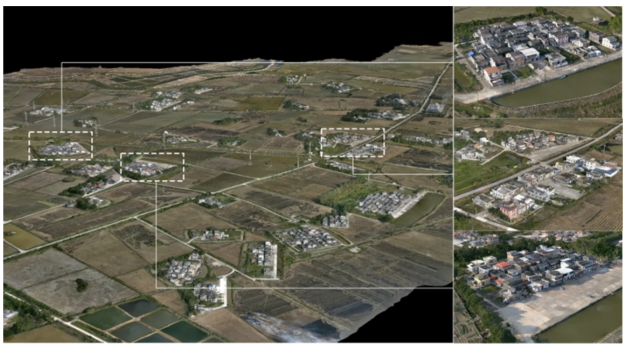

Figure 4. Model of Jiaole Wei case after DJI Terra Processing. The three images on the right illustrate differences in model accuracy between the core area and peripheral areas.

3.2 Meso Scale: Oblique Photogrammetry with a Micro UAV

3.2.1 Oblique Photography Combined with Close-range Photogrammetry (CRP)

For settlement groups and building clusters at the mesoscale, higher-precision models are necessary to represent their spatial morphology and architectural details accurately. At this point, more flexible micro-drones can be used for oblique photography. However, regardless of the method used, single-angle oblique photography has notable limitations, as the angle of aerial photography constrains it. Parts of buildings that are obstructed by other structures are challenging to capture through aerial photography, often resulting in gaps or distortions in the model (Xing, 2023). Especially when dealing with buildings with complex structures such as large eaves and deep verandas, it is difficult to collect data on the facades under the eaves from a high-altitude birds-eye view, resulting in incomplete or distorted models. Additionally, for particularly fine component textures, image resolution may be insufficient to capture the details thoroughly. To address this issue, this study employs oblique photography for basic surveys, combined with close-range photography (CRP) for targeted supplementary measurements (Figure 5). By lowering the flight altitude, the UAV is brought close to the target surface to perform multi-angle photography, or it circles the building to obtain high-definition images at an angle approximately perpendicular to the building's façade (Jiao, 2022). Combining large-scale oblique photogrammetry data with close-range photogrammetry data of key buildings enables the construction of a "selectively detailed" refined model (Li et al, 2017; Zhou et al, 2023).

The case study here used a DJI Mavic 3E（Shenzhen DJI Innovation Technology Co., LTD., Shenzhen, China）, which is a micro four-rotor UAV with a single unit weight of 915g equipped with a 4/3 CMOS 20-megapixel wide-angle camera and a 56x hybrid zoom telephoto camera, offering a maximum flight time of 45 minutes and supporting RTK for centimeter-level hovering precision. The target village cluster is in Guanghai Town, Taishan City, Guangdong Province, characterized by a coastal Guangfu grid-like settlement layout. Its distinctive features include small-scale individual settlements, large distances between settlement groups, and agricultural fields, fishponds as well as other productive lands distributed around the settlements. Each cluster has a highly consistent layout: a regular grid of streets, uniformly arranged building units, an encircling ditch and tree belt, and, at the village entrance, a watchtower.

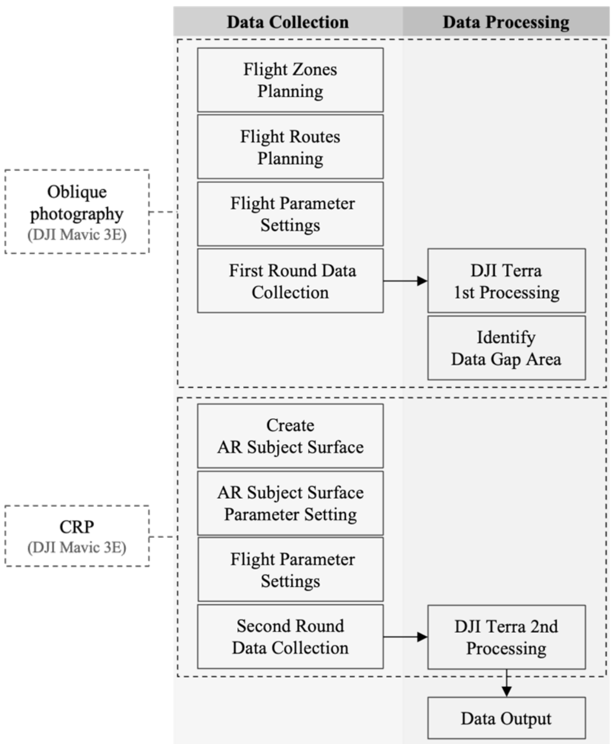

Figure 5. Workflow diagram of combined oblique photogrammetry and Close-Range Photogrammetry surveying

The study selected one of the settlements for surveying. In the first round of oblique photogrammetry, a bow-shaped flight route was planned, with a flight altitude of 70 meters and a ground sample distance (GSD) setting of 1.89 cm/pixel. A total of 743 photos were taken. After preliminary modelling with DJI Terra, the study found that there were serious data gaps in most of the second-floor balconies or platforms of the building units, as well as under the observation platforms protruding from the corners of the watchtowers at the village entrance (Figure 6). Then, the study conducted the second round of supplementary surveying on the watchtower. Using DJI's slope route planning function, a total of ten short flight routes were planned around the watchtower, targeting the missing sections at the lower part of the observation platform. The flight route was maintained approximately 37 metres from the facade, with a height controlled between 16 and 20 metres (Figure 7). The GSD was 1.01 cm/pixel, the fight speed was 15m/s, the side overlap ratio of visible light was 70%, and the forward overlap of visible light was 80% (Table 1).

A total of 77 supplementary photos were taken. The two sets of data were imported into DJI Terra for joint aerial triangulation and modelling. The final model clearly shows the overhanging parts under the watchtower's lookout platforms, as well as details of carved decorations, structural cracks, and material deterioration on the wall surfaces, meeting the accuracy requirements for subsequent building restoration work (Figure 8). It should be noted that although close-range photography can significantly improve model accuracy, it requires a low-speed multi-trajectory flight to cover the target surface, which is time-consuming and inefficient when used over a large area. At the same time, due to the close distance to the building facade, it requires high operational skills.

Figure 6. Model after the first round of oblique photogrammetry

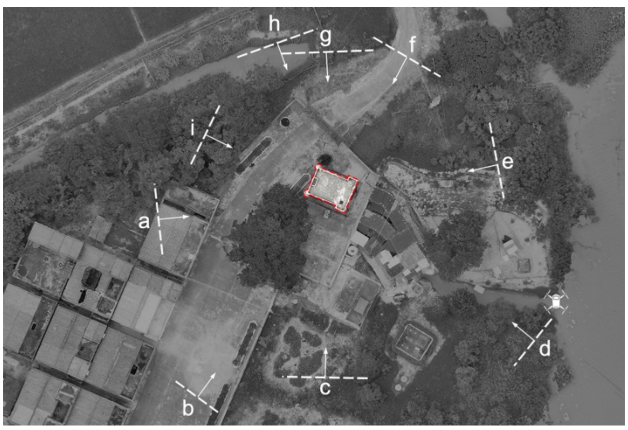

Figure 7. Flight route planning for CRP

Figure 8. The final mesh model of watertower using oblique photogrammetry and CRP methods

Flight Route No.	Lowest Point ASL (m)	Survey Area (m²)	No. of Photos
a	17.5	293	8
b	16.8	217.4	8
c	15.4	412.7	9
d	20.1	216.2	8
e	17.1	511.5	9
f	17.6	347.1	9
g	14.7	405.9	9
i	16.2	221.9	8
h	16.7	493.9	9

Table 1. Flight parameters for different routes in CRP surveying

3.2.2 Terrain-following Flight over Complex Topography

In areas with significant elevation differences, such as mountain villages, traditional fixed-altitude flight methods can result in substantial variations in ground resolution, with insufficient overlap near mountain peaks and excessive overlap in valleys, which can impact model quality. The UAV's real-time terrain-following mode can be used by pre-loading or downloading a high-precision Digital Surface Model (DSM), allowing the UAV to automatically adjust its flight altitude according to the terrain's undulations, maintaining a constant relative height above the ground (Figure 9).

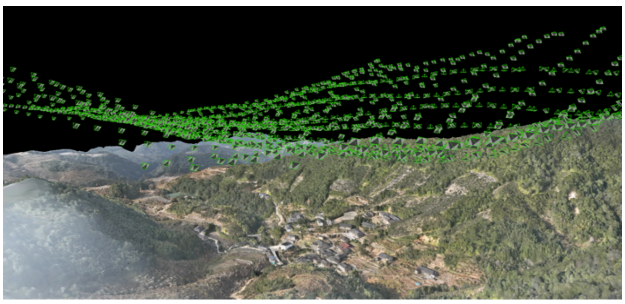

Figure 9. Illustration of photo capture position during real-time terrain following flight

The case study village, Shuizhen Village in Sanming City, Fujian Province, is a typical mountain settlement located in the hinterland of the Daiyun Mountains in central Fujian. The buildings are built along the mountains and rivers, with an overall elevation difference of about 450 meters. For this case, its ecological landscape and mountain-water pattern are key focuses for future conservation, so topographic data needed to be surveyed for later GIS analysis. During the operation, the entire working area was divided into two flight zones, and flight routes were planned. In the flight route parameter settings, the altitude mode was selected as 'relative ground altitude,' and terrain-following flight functionality was enabled. Terrain elevation data was automatically obtained via network download based on the survey area's location. This flight mission set the terrain-following flight altitude to 186 m, the GSD to 5 cm/pixel, and the survey area to 0.78 km². The overall operation generated a total of 1385 images. The final model comprehensively documented the interdependent relationships between villages, terraced fields, and mountainous topography in a mountainous environmental setting, effectively avoiding data quality issues caused by topographical obstructions or uneven resolution (Figure 10).

Figure 10. The final model of Shuizhen Case

3.3 Meso Scale: Small UAV Equipped with LiDAR

Compared to image-based photogrammetry techniques, the Light Detection and Ranging (LIDAR) method demonstrates several advantages. It actively emits laser beams and receives the echoes, directly acquiring high-precision 3D point cloud data of the measured object's surface, with accuracy reaching the millimetre level or better, precisely capturing minute geometric changes on the object's surface. Its unique multi-echo characteristic allows it to partially penetrate vegetation canopies, obtaining real ground point clouds and thereby generating a high-precision Digital Elevation Model (DEM). Therefore, the LiDAR method is suitable not only for analyzing terrain or sites covered by vegetation but also for conducting fine-grained quantitative studies, such as terrain analysis, structural monitoring of buildings, earthwork volume calculations, and forestry resource surveys.

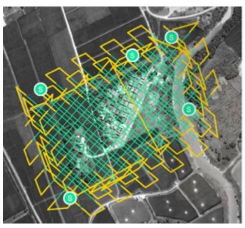

Figure 11. Repeated fights route setting in UAV LiDAR Surveying

Figure 12. The final point cloud model of the case. The red shadow lines in the image below indicate missing data at the water surface

UAV-mounted LiDAR provides another high-precision data source for detailed spatial research at the mesoscale. By integrating a laser emitter, receiver, global navigation satellite systems (GNSS), inertial navigation system (INS), and real-time kinematic (RTK) system, the LiDAR aerial survey system can simultaneously record the position and attitude of each laser point, enabling georeferencing of the point cloud. This combines the high efficiency of UAV operations with the high precision of LiDAR. At the same time, aircraft-mounted LiDAR systems are typically equipped with an auxiliary camera that can attach a colour texture to point clouds, generating a coloured point cloud for later model texture mapping, thus addressing the issue of LiDAR lacking actual colour and texture. At the same time, the images captured by the camera can also be used for two-dimensional or three-dimensional modelling of visible light. However, unlike five-lens cameras that capture five-directional shots simultaneously, drone-mounted Lidar systems typically perform single-direction scanning operations. To obtain complete data on the settlement, building roofs and facades usually requires repeated flights in multiple directions over the target area, making it less efficient than the former method (Figure 11).

The research still utilizes the coastal grid-like settlement in Taishan City, Guangdong Province, as a case study, employing a DJI Matrice 350 RTK UAV equipped with a DJI Zenmuse L2 LiDAR. The Zenmuse L2 is a highly integrated and precise aerial surveying payload that combines a powerful Lidar module, a self-developed high-accuracy inertial measurement unit (IMU), and a 20-megapixel 4/3 CMOS RGB mapping camera. Using LiDAR requires centimetre-level positioning data and high-precision inertial data, so RTK was used during operations. At the same time, the inertial navigation accuracy must be calibrated before data collection to ensure the accuracy of the results. This survey employed a five-echo repeated scanning mode with a sampling frequency of 240 kHz, a ground sample distance (GSD) of 2.15 cm/pixel, a flight speed of 10 m/s, and a point density of 181 points/m². Later, DJI Terra was used to process the three sets of data collected to obtain a 3D point cloud model with accurate colour information.

However, although the model is improved compared to oblique photography models, it still has many limitations. First, LiDAR cannot penetrate water surfaces, resulting in significant data voids in areas with dense water networks, such as rice paddies and fishponds, particularly in the survey case area (Figure 12). Secondly, for narrow streets, building bases, or areas under overhanging structures, UAV aerial scanning still has blind spots, resulting in insufficient point cloud density or data loss. The best solution to this problem is to work collaboratively with ground equipment, such as using handheld 3D scanners for ground and building interiors.

3.4 Meso Scale: Handheld 3D Laser Scanning

Handheld 3D scanners are typically based on Simultaneous Localisation and Mapping (SLAM) technology, integrating modules such as LiDAR, cameras, and IMUs. They enable operators to collect point cloud data with actual colour while walking through the surrounding environment. However, the data from handheld 3D scanners is slightly less accurate than that from terrestrial laser scanners (TLS) (Figure 13). Under similar price conditions, TLS devices such as the Leica BLK360 have an accuracy of 6 mm. In contrast, the Lixel L2 used in this study has a relative accuracy of approximately ±12 mm and a repeat accuracy of less than 20 mm. However, the advantage of a handheld scanner lies in its high flexibility, especially in more complex spaces, where it is more efficient and collects more comprehensive data. Handheld 3D scanners overcome the complexity of frequent setting up of TLS, enabling large-scale data collection of street networks and building facades at the settlement scale in a short time (Figure 14). At the same time, it can also supplement data for areas that cannot be covered by UAV 3D scanning.

Just as UAV oblique photography requires flight route planning and TLS requires point planning, route planning is also crucial during the application process of handheld scanners. Generally, a "closed-loop scan" path should be used to provide constraints for the SLAM algorithm, thereby reducing cumulative error. If practical conditions prevent a closed loop, the OPEN LOOP option must be used during post-processing to avoid distorted and incorrect results. When scanning, the walking speed should be slightly slower than normal walking speed, and the device should be kept moving smoothly to avoid insufficient point cloud density or blurred images. In addition, environments with significant differences between indoor and outdoor lighting pose a major challenge for point cloud colouring. Operations should avoid strong top-down or back-lit conditions, choosing overcast days or twilight hours for outdoor scanning and ensuring sufficient, stable lighting indoors. This study employed the Lixel L2 to conduct precise data collection of the street spaces in the coastal grid-like settlement case, supplementing the missing bottom portion of buildings in the UAV laser point cloud model. Lixel L2 is a handheld real-time 3D reconstruction device developed by XGRIDS (Shenzhen XGRIDS Innovation Technology Co., Ltd., Hong Kong, China). It integrates LiDAR, a three-colour camera, high-precision inertial navigation, and a high-performance computer that can combine data capture with real-time modelling.

When the fieldwork was done, Lixel Studio was used to calculate the point cloud. After optimizing the point cloud mapping, dynamic object removal, filtering, and colouring, human-perspective point cloud data was output. Then, Trimble RealWorks was used to register and merge the two sets of point clouds, outputting a complete and detailed point cloud dataset (Figure 15). The model demonstrates that by combining UAV point cloud scanning with handheld point cloud scanning, a comprehensive dataset can be obtained, encompassing the ground, walls, and roof (Figure 16).

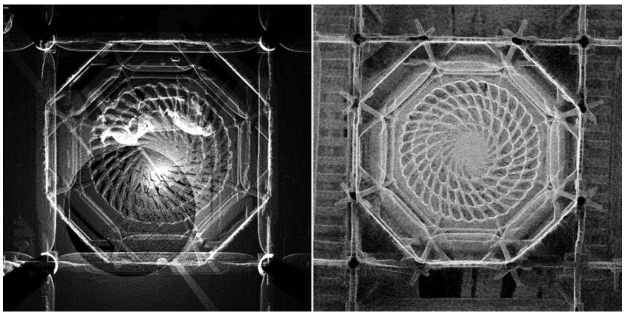

Figure 13. Comparison of scanning results for the same ancient Chinese architectural ceiling using TLS (left, Leica BLK360) and a handheld scanner (right, Lixel L2)

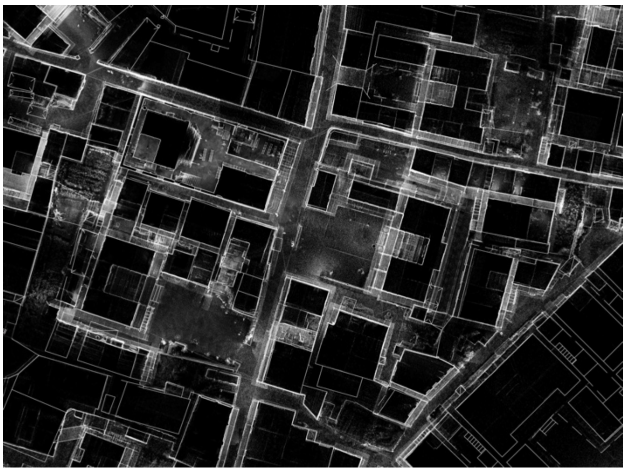

Figure 14. Village plan scanned with a handheld scanner

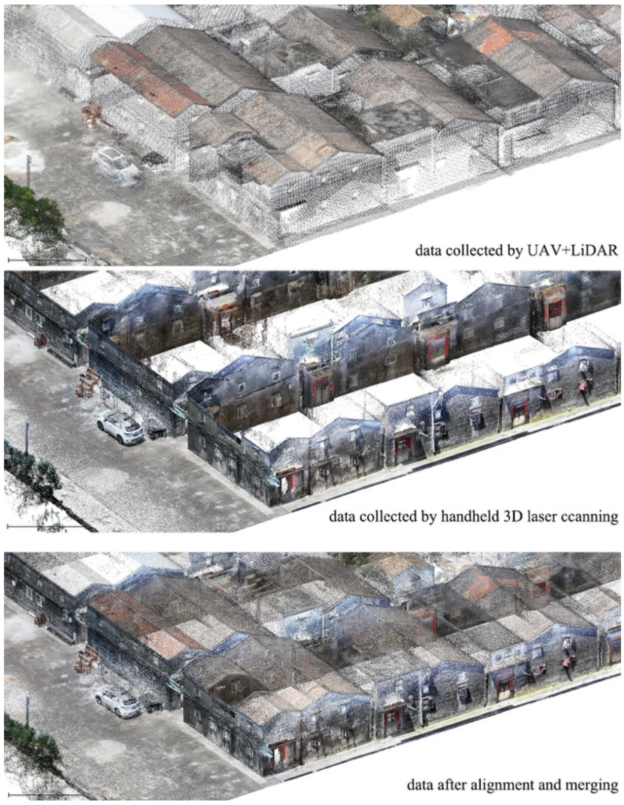

Figure 16. The roof section obtained from the UAV laser scanning was merged with the bottom half of the village and buildings scanned by the handheld scanner to generate a fully integrated model.

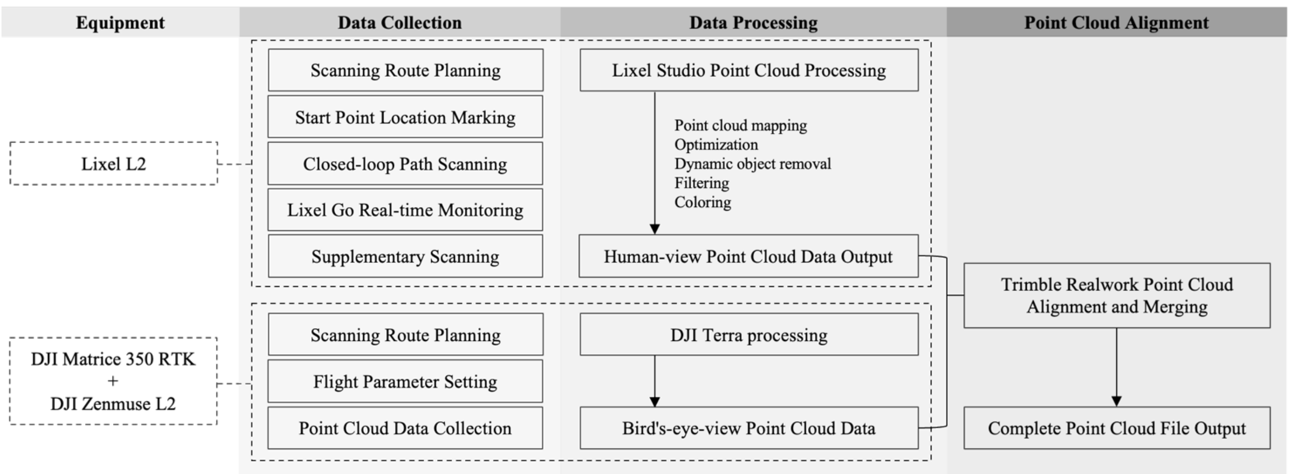

Figure 15. Workflow diagram of combined Handheld 3D Laser Scanning and UAV LiDAR scanning

3.5 Micro-scale: Metrology-grade 3D Scanner

For micro-scale features, such as details and textures, a metrology-grade 3D scanner is used for fine collection. In this study, the Kscan Magic II (SCANTECH (HANGZHOU) CO., LTD., Hangzhou, China) composite 3D scanners were employed, which integrate cutting-edge composite 3D scanning technology with infrared and blue laser technology.

Under hyperfine scanning mode, it achieves a maximum resolution of 0.01 mm, enabling the capture of complete surface data for complex objects and accurately capturing the object's intricate geometric shapes and surface texture details. However, the price of high precision is a small scanning range, low operational efficiency, and the need for an external power source and computer for operation, which limits mobility. Another challenge is the placement of target markers. To accurately merge small-scale data from multiple scans into a single, cohesive image, encoded target points must be affixed to the surface or surrounding area of the object being measured. On objects with extremely irregular and uneven surfaces, it is difficult for reflective sheets or target points to adhere completely, resulting in registration errors that affect the detail of the final model. This is especially problematic when working outdoors, where the condition and cleanliness of the object being measured may not be ideal, further affecting target point placement.

This study digitized the oyster shell heritage in Daling Village, Panyu, Guangzhou. As can be seen, due to the numerous and deep depressions in the arrangement of the oyster shells, even though enough targets were placed, many voids were still generated after scanning, requiring post-processing data correction (Figure 17).

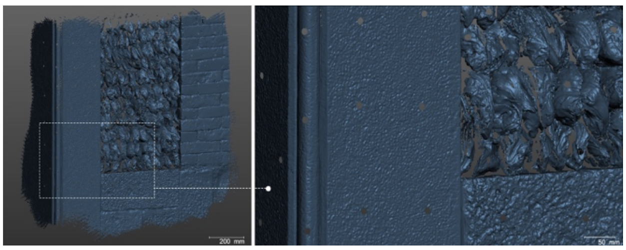

Figure 17. Data missing due to the uneven shape of oyster shells

4. Integrated Application Strategy and Framework Construction for Multi-scale Technologies

4.1 Comparative Analysis of Different Technological Methods

Through the practical application and analysis of these cases, it becomes apparent that different technologies exhibit significant variations and complementary characteristics in terms of application scenarios, advantages, and limitations. Both UAV oblique photogrammetry and UAV laser scanning can effectively cover large areas. However, the former has advantages in terms of real texture but suffers from data bias when dealing with complex structures and special areas, while the latter can penetrate vegetation to obtain more accurate ground information but is expensive and falls short of obtaining colour texture information and image details; Micro UAVs for close-range photography and handheld scanners can supplement detailed and concealed spatial information. The former focuses on acquiring high-resolution texture models, while the latter is more suitable for comprehensive scanning of complex structures, offering high flexibility and adaptability. However, both have relatively limited scanning ranges and lower efficiency, making them unsuitable for large-scale tasks without additional support. The Metrology-grade 3D scanners provide ultra-high precision and detailed data, making them suitable for recording valuable artefacts and fine components. However, they operate at the most minute scale, with high time costs and numerous environmental limitations.

4.2 Technical Framework

Based on an in-depth analysis of the multi-scale characteristics of traditional village heritage and a systematic comparison of different digitalization techniques, this study proposes a digital surveying technical framework, 'dynamic hierarchical collecting—multi-device collaborative operation—cross-scale integration'. This involves implementing a hierarchical, dynamic acquisition strategy based on the object's scale and complexity during the data acquisition phase, adopting a collaborative operation of air and ground multi-platforms to organize the work, and achieving a unified fusion of data from different scales in the data processing phase.

4.2.1 Dynamic Hierarchical Collection

Based on the importance and scale differences of spatial information within the survey area, adjust the resolution, accuracy, and coverage of data collection flexibly to ensure optimal results. For example, for macro-scale settlement landscapes, the focus is on the overall layout and spatial relationships, so relatively low data accuracy can be used; for mesoscale building groups and street spaces, medium-accuracy geometric information and texture details are required; for micro-scale important components and decorative details, the highest accuracy data collection methods must be used.

When conducting large-scale aerial photography of villages, the resolution and overlap of core areas are increased. In contrast, the sampling density of peripheral secondary areas is reduced, thereby ensuring accuracy in key areas while maintaining overall efficiency. This layered collection method, based on region and scale, ensures that key heritage elements are recorded in detail. At the same time, non-essential parts are collected more efficiently, thereby optimizing the overall data volume and processing costs.

4.2.2 Multi-device Collaborative Operation

Fully leverage the advantages of different surveying platforms and sensors by using multiple devices to complete the survey task collaboratively. In village heritage surveying, aerial platforms (such as UAVs with multi-lens cameras and UAVs with LiDAR) and ground platforms (such as handheld mobile scanners) can work together simultaneously or in stages. UAVs are responsible for acquiring data at the macro and mesoscales, quickly covering large areas and capturing the external morphology of buildings. Ground-based or indoor scanning devices, on the other hand, focus on the microscale to supplement details and structural data. Multi-platform collaboration can address blind spots that a single platform cannot cover, such as narrow streets or indoor spaces that drones cannot access, for which handheld scanners are ideally suited. Conversely, large-scale surveying is inefficient when using only handheld devices, whereas UAV aerial surveys are significantly more efficient. Through a reasonable division of labour and collaboration, full coverage of the survey area and a complete collection of multi-scale information can be achieved.

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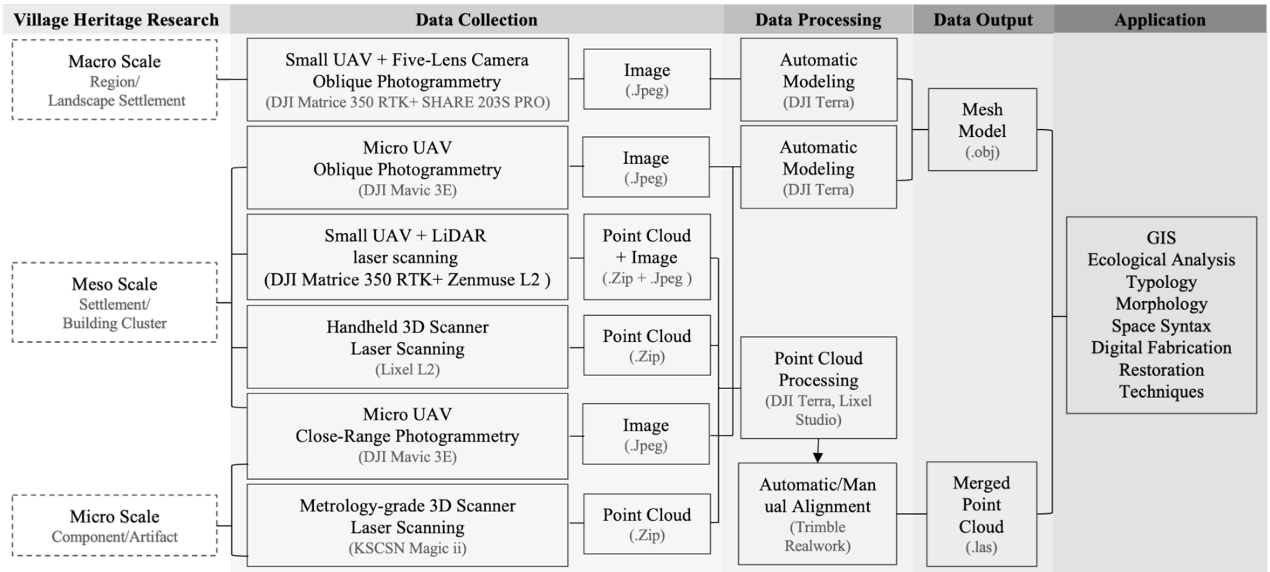

Figure 18. Workflow and methods for documenting and visualising spatial information of village heritage based on 3D Digital Technologies

4.2.3 Cross-scale Integration

During the data processing and modelling stage, data from various devices and scales are unified in a standard coordinate system and integrated into models. Data from each scale is georeferenced using methods such as setting common control points, GNSS, and RTK positioning, and then 3D models are constructed through data fusion algorithms. In future applications, the result of cross-scale fusion will be a digital model that not only contains the overall spatial framework of the village but also presents the details of the buildings with meticulous accuracy. This is the foundation for building "digital twin" scenarios or multi-level detail rural heritage databases (Figure 18).

5. Conclusion

This study systematically analyses the multi-scale characteristics of traditional village heritage and proposes an integrated application strategy for digitalization techniques adapted to different scales. The study indicates that the complexity of traditional village heritage makes it difficult for a single technical method to meet the requirements for comprehensive documentation. Instead, an effective digital documenting and conservation process must be achieved through the organic integration of multiple technologies. The construction of a comprehensive technical framework based on the 'dynamic hierarchical collection—multi-device collaborative operation—cross-scale integration' approach provides a systematic solution for the digital conservation of traditional village heritage. The integrated application of multiple technologies not only enhances the efficiency and quality of digital documentation but, more importantly, elevates the protection of village heritage from traditional, static surveying and documentation to a multi-layered, dynamic digital management model. Under this model, information at different scales can be cross-verified and updated, enabling the creation of digital twins of heritage features. This provides data support for subsequent monitoring and early warning, virtual exhibitions, and restoration simulations.

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