Methodology and Practice of Hong Kong 3D Digital Map Construction Based on Multi-Source Data Fusion

Li Chen, Jun Li, Yaping Wang, Jing Wang, Weichen Yao

Shaanxi TIRAIN Science & Technology Co.,Ltd., Xi’an, Shaanxi, China - chen@trgis.com, lijun@trgis.com, ypwang@trgis.com, wangjing@trgis.com, yaoweichen@trgis.com

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ABSTRACT

In response to Hong Kong's smart city development strategy, this paper takes the 3D digital map construction project in Kowloon as a practical case study and systematically presents a construction method for 3D digital mapping based on multi-source data fusion. Aiming at the technical challenges in high-density urban environments-including dense buildings, complex 3D traffic networks, and severe shadow occlusion-an "air-ground fusion" data acquisition strategy is proposed. By comprehensively adopting multiple approaches such as oblique aerial photography, Vehicle Mobile Mapping System (VMMS), and Portable Mobile Mapping Survey (PMMS), a high-precision and highly realistic urban 3D model has been constructed. The paper focuses on the principles of multi-source data fusion based on feature registration and combined adjustment, as well as the 3D modeling process and the quality control methods for the final results. The project’s technical innovation and practical feasibility have been validated through international benchmarking. The research results have been applied to urban planning, traffic management, environmental studies and other fields, providing a solid data foundation and technical support for Hong Kong's smart city development.

1. Introduction

With the rapid advancement of smart city development, 3D digital maps, as the core foundation of City Information Model (CIM) and digital twin cities, have become a major research focus in the international geographic information community. Internationally, the Netherlands' 3DBAG project is a typical example of national-level 3D city modeling, and has been widely applied in urban climate simulation, energy analysis and related fields (Kadaster, 2023; Khoo, 2020). Multiple studies have enhanced the semantics of the 3DBAG model to support more refined simulation of the urban heat island effect and analysis of energy consumption (Buyukdemircioglu and Oude Elberink, 2025). Virtual Singapore is the world's first national-level digital twin platform, it constructs 3D semantic models covering 12 major categories of urban features and integrates real-time IoT data to support intelligent applications such as traffic management, energy optimization and emergency evacuation (GovTech Singapore, 2017; Nazim and Joyce, 2024).

In China, with the advancement of real-scene 3D China, city-level realistic 3D modeling has become a major research focus. Zhu et al. systematically reviewed multi-point-cloud data fusion methods for 3D city modeling and pointed out that feature registration and combined adjustment are key to achieving high-precision multi-source data fusion (Zhu et al., 2018). Zhou investigated the refined modeling methods based on multi-source data fusion, and discussed the collaborative processing strategies for oblique photography and terrestrial laser scanning data (Zhou, 2025). In addition, Zhu et al taking Zhongshan City as a case study, effectively addressed challenges such as large data volume, complex terrain and model deformation caused by line-of-sight occlusion (Zhu et al., 2024). Zeng et al. studied high-precision urban modeling technology integrating with laser point clouds, achieving an integrated representation of buildings, roads, vegetation and other urban elements (Zeng et al., 2023). Hua et al. further explored the technical approaches for refined modeling and visualization to meet the modeling needs of large-scale central urban areas (Hua et al., 2023). However, most existing studies focus on individual technical stages or small and medium-scale regions. For typical high-density urban areas characterized by ultra-high building density, complex 3D traffic systems, and severe shadow occlusion, systematic research and practice on the integrated acquisition and fusion of airborne, vehicle-borne, and backpack-borne multi-source data remain scarce.

As a typical high-density and complex urban area, Kowloon, Hong Kong, faces not only the dual challenges of ensuring geometric completeness and visualization in the construction of 3D digital maps, but also the need to provide a high-precision data foundation for subsequent digital twin applications. Therefore, taking Kowloon as a pilot area, this paper systematically presents a 3D digital map construction method based on multi-source data fusion, It focuses on the overall technical framework of The Project, methods for multi-source data acquisition and processing, phased practical results and application prospects, aiming to provide a referable technical paradigm for digital modeling of similar high-density cities.

2. Regional Overview and Technical Route

2.1 Regional Overview

The project area covers East Kowloon and Central Kowloon, with an area of approximately 51 km², including a land area of about 41 km², about 660 km of roads, approximately 630

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infrastructure facilities (including viaducts, footbridges, tunnels, etc.), and about 16,000 buildings. East Kowloon is the first pilot area for 3D digital map development under the smart city and complex 3D relationships of facilities such as overpasses and tunnels. The dense distribution of super high-rise buildings presents obvious vertical characteristics, forming complex occlusion relationships, which pose severe challenges to the geometric integrity of 3D modeling and the processing of dynamic shadows. There are many landmark buildings in the area, such as Kai Tak Cruise Terminal, Construction Industry Council Zero Carbon Park, East Kowloon Government Offices, etc., which require more refined modeling standards to be presented with more detailed and realistic models. In addition, Kowloon covers a variety of typical urban textures, including initiative promoted by the Government of the Hong Kong Special Administrative Region. The area is characterized by dense buildings, narrow streets, numerous high-rise buildings, newly built high-quality building complexes and dense old industrial and commercial areas. This diverse and mixed urban form imposes differentiated requirements on 3D modeling. In view of the regional characteristics of Kowloon, sufficient research and analysis were carried out in the early stage of the Project, and specific technical requirements for modeling were developed for each key issue, thereby providing basic conditions for formulating the overall technical framework of the Project. The regional characteristics and corresponding technical requirements are presented in Table 1.

Work Area Characteristics	Technical Requirements for Modeling	Corresponding Indicators
Ultra-high building density and severe occlusion	Multi-source data fusion (oblique photography + laser scanning) is mandatory	Geometric integrity, building facade quality
Complex aerial corridors and 3D transportation	High-precision point cloud registration to ensure accurate spatial topological relationships	Geometric integrity
Dense high-rise buildings and significant dynamic shadows	High temporal dimension modeling	Depth of model application
Landmark buildings requiring detailed presentation	Multi-level modeling accuracy (differentiated LOD processing)	Visualization

Table 1. Analysis of Work Area Characteristics and Modeling Technical Requirements

2.2 Technical Framework

Based on the above analysis, the Project first acquired raw data, including oblique aerial images, vehicle-mounted laser point clouds, backpack laser point clouds, panoramic images and close-range individual images, through means such as oblique aerial photogrammetry, VMMS and PMMS, aerial triangulation is then performed on the oblique aerial images, while SLAM-based joint processing was carried out for the laser point cloud data. Subsequently, multi-source vector data fusion was conducted, along with mapping relationship estimation, color balancing, and data fusion for the acquired aerial images, panoramic images, and individual images. Based on the processed multi-source data, digital products such as 3D individual models, True Digital Orthophoto Maps (TDOM), and Digital Surface Models (DSM) were generated. After quality inspection, the final project deliverables were released on a data display platform to provide dataset download, query, and browsing services for the government and the public. The project's technical framework is illustrated in Figure 1.

3. Data Acquisition Strategy and Methods

3.1 Data Acquisition Strategy

In the view of the characteristics of high density, complex 3D structures and pervasive shadow effects in Kowloon, Hong Kong, the following methods are adopted in the data acquisition stage:

(1) The Project generally adopts the "air-ground integrated" method. The top and overall outline of buildings are acquired through airborne oblique photogrammetry, while the ground and bottom facades of details are supplemented by VMMS/ PMMS to ensure geometric completeness and to solve the problems of model "blurring" and distortion caused by narrow streets.

(2) For infrastructure with complex three-dimensional relationships such as overpasses, footbridges and tunnels, we mainly use data acquired by VMMS/PMMS, and adopt aerial images and field photos captured by MMS as texture sources. This ensures clear textures on the bottom and sides of overhead structures and accurately represents 3D spatial topological relationships.

(3) During aerial photography, flights operations should be carried out under conditions of uniform illumination (such as on cloudy days or noon with sufficient sunshine) to reduce texture misalignment and color inconsistency caused by reflections from large-area glass curtain walls and by shifting shadow. For areas with repetitive textures (such as dense residential areas), the image overlap ratio should be appropriately increased.

(4) During control survey, the Hong Kong CORS network was directly used in areas with open visibility and good signal reception, and the network RTK method was adopted for control measurement; in areas with weak or unavailable CORS signal, traverse survey was used for control survey.

3.2 Data Acquisition System

Aiming at the characteristics of high-density environment and complex 3D space in Kowloon, Hong Kong. The Project establishes an "air-ground" integrated, multi-platform collaborative data acquisition system. The system comprehensively employs oblique aerial photogrammetry, VMMS, PMMS, high-precision control survey and other technical means to achieve full-coverage and high-precision 3D data acquisition from the top to the bottom of buildings, from main roads to back streets and alleys, thereby laying a solid foundation for subsequent multi-source data fusion and refined modeling.

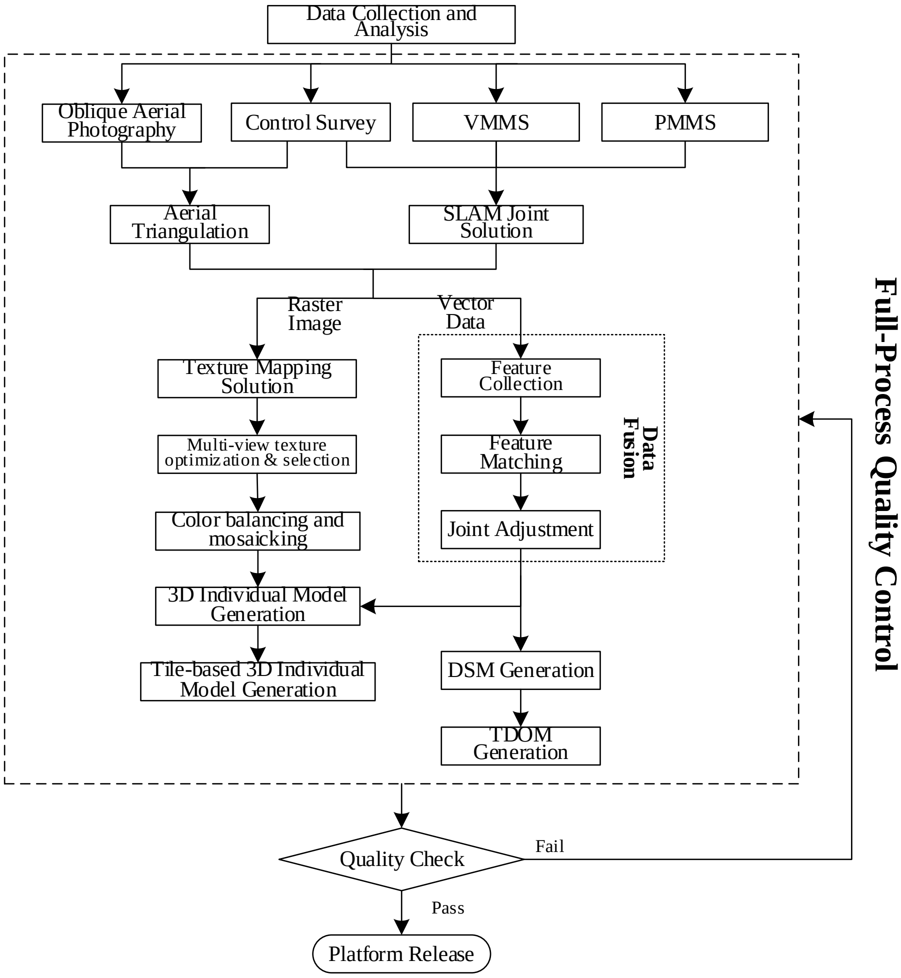

Figure 1. Technical Framework

3.2.1 Oblique Aerial Photography: A helicopter equipped with an SWDC-Max6Ap150 oblique camera was used to perform oblique aerial photography over a 45 km² land area. The system is equipped with 6 Phase One cameras, including Two nadir lenses (150 megapixels each) and four oblique cameras (150 megapixels each), the survey was carried out with an average endlap of 75%, sidelap of 70%, and ground resolution of 0.055 m.

3.2.2 Vehicle Mobile Mapping: The SSW vehicle-mounted mobile mapping system was used to conduct VMMS surveys on approximately 580 km of roads, acquiring road laser point clouds, panoramic images, and individual images. As a new-generation high-tech mobile mapping system for the rapid acquisition and processing of full-element data, it integrates multiple sensors, including GNSS, INS, DMI, Riegl scanner, Ladybug5+ panoramic camera, and six 36-megapixel DSLR cameras. It is a high-performance survey-grade mobile mapping system for holographic 3D modeling, both domestically and internationally.

3.2.3 Backpack Mobile Mapping: The BMS3D backpack mobile mapping system was used to perform PMMS on buildings, footbridges, underpasses, etc. in designated areas, acquiring laser point clouds and panoramic images. Integrated with GNSS, INS, SLAM, Ladybug5+ panoramic camera and other equipment, the system can efficiently collect 3D data in narrow streets and pedestrian areas, effectively compensating for the operation blind spots of vehicle-mounted or airborne systems.

3.2.4 Control Survey: Control survey includes both control points and check points. Control points are used for the correction of oblique aerial images, vehicle-mounted laser point clouds and backpack laser point clouds, while check points are used for the inspection of corrected results. Control points are uniformly arranged at intervals of no more than 100 m, and check points are distributed at a density of at least 4 points per kilometer. In areas lacking distinct feature points, an appropriate number of additional horizontal and elevation control points can be established to improve the accuracy of point clouds.

4. Data Processing

4.1 Data Fusion Method

As the project involves three types of data sources: oblique photogrammetric imagery, VMMS, and PMMS, ensuring high-precision registration of multi-source data is critical to its success. This project mainly adopts feature-based registration algorithms and joint adjustment methods to unify airborne imagery and vehicle-borne LiDAR point clouds into the same coordinate system, thereby avoiding model layering and misalignment.

4.1.1 Feature-based Registration Method: Aiming at heterogeneous data fusion between vehicle-borne LiDAR point clouds and airborne oblique imagery in the high-density urban area of Kowloon, a geometric feature-based registration method is employed. Common features extracted from multi-source data are used as registration primitives to achieve data unification under different coordinate systems. The detailed procedures are as follows:

(1) Feature extraction. Plane features (building facades, road surfaces), linear features (building outlines, road edges) and pole-like features (street lamps, traffic sign poles) are extracted separately from airborne oblique imagery and vehicle-borne LiDAR point clouds. Plane features are robustly estimated using region-growing algorithm combined with RANSAC, while pole-like objects are identified through spatial clustering and geometric morphology analysis.

(2) Feature matching. Based on extracted features, coarse matching is performed using an improved ICP algorithm integrated with geometric constraints. For plane features, the angle between normal vectors and plane distance are used as similarity metrics; for pole-like objects, spatial position and height serve as matching criteria. To address occlusion caused by narrow streets in Kowloon, multi-view geometric constraints are introduced to prioritize features with less occlusion in solution computation.

(3) Transformation parameter estimation. Rigid transformation parameters (rotation matrix R and translation vector T) are solved using quaternion method based on matched feature pairs. To improve robustness, the PROSAC algorithm is applied to remove mismatches and ensure high-confidence features for parameter estimation.

(4) Fine matching optimization. On the basis of coarse registration, a sub-pixel matching algorithm based on Zero-mean Normalized Cross-Correlation (ZNCC) is adopted for fine alignment of corresponding features between imagery and point clouds, achieving sub-pixel registration accuracy. Experiments show that this method yields a planar root-mean-square error (RMSE) ≤ 0.10 m in complex scenarios of Kowloon.

The advantage of this method lies in its independence from precise point-to-point correspondence in point clouds. Instead, high-level geometric features are used for constraint, which effectively resolves issues such as large viewing-angle differences and inconsistent point density between airborne and vehicle-borne data.

4.1.2 Combined Adjustment Method: After completing feature-based coarse registration, this project further adopts the combined adjustment method to incorporate multi-source observations into a unified mathematical model for global optimization, thereby achieving a transition from simple geometric alignment to integrated parameter fusion.

(1) Observation types and mathematical model: The observations for combined adjustment include three categories: image observations (pixel coordinates of oblique imagery), LiDAR observations (coordinates of vehicle/backpack point clouds), and POS observations (sensor pose parameters provided by GNSS/IMU). An extended bundle block adjustment is adopted as the mathematical model, which uniformly represents various observation equations as follows:

$$\begin{cases} x_{ij} = P_i\left(X_j\right) + e_{ij} & \text{(Image observation)} \\ L_{kj} = R_k X_j + T_k + v_{kj} & \text{(LiDAR observation)} \\ S_i = S_i^0 + w_i & \text{(POS observation)} \end{cases} \quad (1)$$

Where x_{ij} is the image point coordinate of the j^{th} object point on the i^{th} image,
P_i is the projection function of the image,
X_j is the coordinate of the object point,
e_{ij} is the residual of the image observation;
L_{kj} is the coordinate of the j^{th} point observed by the k^{th} laser scanner,
R_k and T_k are the rotation matrix and translation vector of the laser scanner,
v_{kj} is the residual of the LiDAR observation;
S_i is the sensor pose parameter at the i^{th} moment,
S_i^0 is the initial pose provided by the POS,
w_i is the residual of the POS observation.

(2) Weight determination: The core challenge in combined adjustment lies in reasonably determining the weights for different types of observations. In this Project, the Helmert variance component estimation method is adopted to iteratively calculate the posterior variance components of various observations and realize optimal weight determination. The procedure is as follows:

- Assign initial empirical weights to different observation types: Imagery : LiDAR : POS = 1: 10: 5;
- Perform the first adjustment and compute the sum of squared residuals for each observation type;
- Update the variance components and re-determine the weights according to the Helmert formula;
- Iterate until the variance components converge (typically 2 to 3 iterations).

Experimental results from the Kowloon project show that the weight ratio between imagery and LiDAR finally converges to 1: 8.5, which is consistent with the nominal accuracy of the sensors.

(3) Total Least Squares extension: To overcome the limitation of traditional joint adjustment that assumes error-free coefficient

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matrices, the Total Least Squares (TLS) method is introduced with an Errors-in-Variables (EIV) model, which optimizes errors in both observations and coefficient matrices simultaneously. Theoretically, TLS provides more reliable parameter estimates than conventional least squares in multi-source heterogeneous data processing.

(4) Implementation workflow: Taking the sparse visual point cloud from aerial triangulation of oblique imagery as the reference, vehicle/backpack LiDAR point clouds are registered to this reference via an improved spatial consistency method. Different adjustment strategies are then applied according to whether visual points are covered by LiDAR:

- LiDAR-observed regions: dominated by LiDAR geometric constraints;
- LiDAR blind areas: dominated by dense image matching.

This strategy fully exploits the textural advantage of imagery and the geometric advantage of LiDAR.

Through the combination of feature-based registration and joint adjustment (the technical combination mentioned above), this project has achieved high-precision fusion of airborne oblique imagery and vehicle-borne/backpack-borne LiDAR point clouds. Verified using check points, the root mean square errors (RMSE) of the fused point clouds are as follows:

- Planar RMSE: 0.05 m (VMMS), 0.08 m (PMMS);
- Elevation RMSE: 0.04 m (VMMS), 0.10 m (PMMS).

These results fully verify the effectiveness of the proposed fusion method.

4.2 Production of 3D Individual Object Model

Based on oblique aerial imagery, LiDAR point clouds, panoramic images, individual images and topographic map data, individualized modeling is conducted for seven categories of features: buildings, infrastructure, vegetation, sites, water bodies, terrain and general objects.

4.2.1 Individual Building Models: Building structures are mainly generated from oblique 3D models and LiDAR point cloud data (Shi, 2016). Outline and 3D vector data of roof structures are collected from oblique 3D models, and white models and texture mapping are completed in software such as SVS Modeler and DP Modeler, with textures mainly derived from oblique aerial imagery.

For areas where building structures are distorted due to occlusion or other reasons, VMMS point clouds are used to supplement building geometry. Building bottom textures are mainly extracted from panoramic images using a multi-view texture optimization algorithm, and then colour-balanced and fused with oblique imagery textures to ensure natural colour transition at seams and realistic visual effects. The final effect of the Individual Building Models is illustrated in Figure 2.

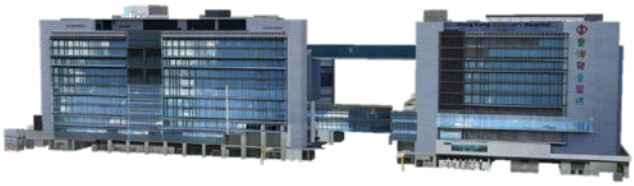

Figure 2. Individual Building Model

4.2.2 Individual Infrastructure Models: Infrastructure such as viaducts, tunnels, footbridges, and underpasses are individually modeled and classified by feature type. Structural data collection of infrastructure elements is mainly conducted using VMMS data, while PMMS data is used to supplement the areas not scanned by VMMS.

Textures for road surfaces, railway surfaces, and viaduct decks are generated from oblique aerial imagery; the side faces of viaducts and other infrastructure models are textured using individual images acquired by VMMS. The final effects of some individual infrastructure models are shown in Figure 3.

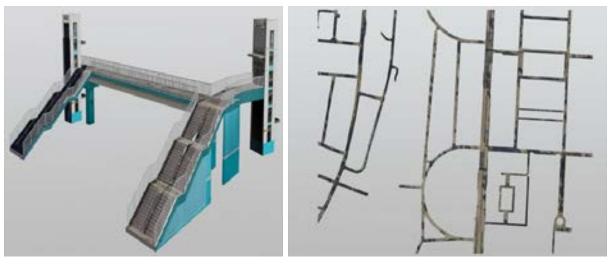

Figure 3. Infrastructure Individual Model

4.2.3 Vegetation, Site, Water Body and Generics Individual Models: Based on oblique 3D models and VMMS data, and with reference to topographic map data, we draw and collect 3D vector lines for features including vegetation, sites, water bodies, roads, and isolation facilities. A TIN is then constructed and white models are generated. Texturing is mainly performed using True Digital Orthophoto Map (TDOM) products. Specifically, site models are produced by clipping the oblique 3D models with boundary lines in software such as SVS Modeler and DP Modeler, flattening building and infrastructure elements in the clipped results, and then merging the individual building and infrastructure models. The final effect of such individual models is shown in Figure 4.

4.2.4 Individual Terrain Models: For the terrain individual model, 3D vector data of road features (including road edge lines and road surface elevation points) are first collected mainly from VMMS scanned point cloud data. Then, 3D feature points and lines at terrain change locations-such as scarps, slopes, ridges, valleys, and water systems-are collected mainly from oblique 3D models. Next, a TIN is constructed and clipped according to the B1000 standard map frame. After clipping, a white model of the individual terrain model is generated, and finally, texturing is performed using TDOM. The final effect of the individual terrain model is shown in Figure 5.

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Figure 4. Vegetation, Site, Water Body and Generics Individual Models

Figure 5. Individual Terrain Model

4.3 Result Quality Analysis

All tasks for the Generation of 3D Digital Map in East Kowloon were completed by the end of 2021, verifying the technical route and the required indicators. Based on the experience gained from the East Kowloon Project, the Generation of 3D Digital Map in the Central Kowloon was carried out in 2022. Practical results are presented as follows.

4.3.1 Geometric Accuracy Statistics: A total of 17 km² was covered by oblique aerial photography using a helicopter-borne SWDC-Max6Ap150 oblique camera. The SSW vehicle-borne mobile mapping system was used to acquire data along 363 km of roads, and the BMS3D PMMS system was applied to collect data of buildings and infrastructure covering 60 km. In total, 7,700 control points and 4,050 check points were surveyed. The accuracy statistics of the final deliverables and intermediate products are presented in Table 2.

No.	Results		Planar RMSE	Elevation RMSE
1	3D Individual Mode	Building	0.13m	0.16m
		Infrastructure	0.14m	0.02m
		Vegetation	0.11m	0.08m
		Sites	0.14m	0.10m
		Waterbody	0.15m	0.14m
		Generics	0.14m	0.08m
		Terrain	--	0.11m
2	Tile-based 3D Individual Model		0.10m	0.07m
3	TDOM		0.22m	--
4	DSM		--	0.15m
5	Georeferenced Point Cloud	VMMS	0.05m	0.04m
		PMMS	0.08m	0.10m
6	Georeferenced Panoramic Image	VMMS	0.05m	0.04m
		PMMS	0.08m	0.10m
7	Control Points, Check Points		0.03m	0.06m

Table 2. Geometric Accuracy Statistics of Central Kowloon Deliverables

The above practice results are significantly better than the designed technical indicators and conform to the actual situation of Hong Kong. Currently, the production of 3D digital maps for the remaining areas of the entire territory is in progress.

4.3.2 International Horizontal Comparison

A comparative analysis was carried out against existing national-level 3D projects such as 3DBAG (Netherlands) and Virtual Singapore, in terms of geometric completeness, building facade quality, and visual appearance, as presented in Table 3. With the exception of a few indicators, most have reached or even exceeded those of comparable projects, demonstrating an internationally leading standard.

Evaluation Dimension	3DBAG	Virtual Singapore	Hong Kong (Kowloon)
Geometric Completeness	LOD1.2-2.2	LOD2-3	LOD2-3
Planar Accuracy	10-25 cm	5-10 cm	11-15 cm
Elevation Accuracy	15-30 cm	10-15 cm	2-16 cm
Facade Quality	Medium (mainly parametric)	High (fine texture mapping)	Medium-High
Texture Resolution	5-10 cm GSD	2-5 cm GSD	2-10 cm GSD
Visualization	Medium (orthophoto texture)	High (multi-source fusion texture)	High (multi-source fusion texture)

Table 3. Horizontal Comparison of Project Quality

5. Conclusion

This paper systematically explores and discusses the construction methods and practical pathways of the Hong Kong 3D Digital Map, with Kowloon as the pilot area. Focusing on high-density urban environments, we conduct in-depth research on multi-source data fusion, refined modeling, and result quality control. The project exhibits certain innovation and demonstration significance in technical route design, data acquisition strategy, and fusion algorithm application, possessing considerable research value and practical significance.

The successful implementation of the project in Kowloon verifies the applicability and reliability of air-ground fusion and joint adjustment technologies in complex urban environments, providing a replicable and promotable technical paradigm for the subsequent construction of 3D digital maps in the New Territories and other regions of Hong Kong. The project achievements have been effectively applied in fields such as land surveying, urban planning, traffic management, and environmental monitoring, providing open and shared spatial data resources for the public, academia, and enterprises, and promoting the development of the digital economy and the realization of the smart city blueprint.

In the future, with the continuous advancement of artificial intelligence, real-time modeling, and digital twin technologies, 3D digital maps will expand from static presentation to the direction of dynamic perception and intelligent analysis, becoming an important supporting platform for urban governance and public services. Hong Kong's exploration and practice in this field not only lay a solid foundation for its own smart city construction, but also provide valuable insights and references for the digital governance of high-density cities worldwide.

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