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Application Strategies of UAV-GIS Digital Topographic Mapping

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Abstract: *As the surveying, mapping, and geoinformation industry accelerates its digital and intelligent transformation, conventional manual surveying methods relying on total stations and GPS-RTK (global positioning system real-time kinematic) are increasingly inadequate for meeting the demanding requirements of high-precision and high-efficiency topographic data in domains such as territorial planning, engineering construction, geological exploration, and emergency mapping. These traditional approaches are commonly plagued by limited operational efficiency, poor adaptability to complex terrains, high labor costs, and untimely data updates. In contrast, unmanned aerial vehicle (UAV) photogrammetry offers exceptional maneuverability, low operational costs, and rapid map production, enabling efficient large-area topographic data acquisition. Meanwhile, geographic information system (GIS) technology excels in spatial data processing, analysis, storage, and visualization. The deep integration of these two technologies has become a mainstream paradigm for digital topographic mapping. Based on real-world production scenarios, this paper systematically reviews the technical principles and standardized workflows of UAV-GIS collaborative mapping, summarizes existing challenges in accuracy control, data fusion, and process management, and proposes practical optimization strategies derived from engineering experience. The aim is to further enhance the precision, efficiency, and practical value of topographic mapping products, thereby providing actionable technical references for the digital upgrading of the surveying and mapping industry.*

Keywords: *UAV photogrammetry; GIS technology; digital topographic map; mapping accuracy*

1. Introduction

Digital topographic maps serve as indispensable foundational geoinformation carriers for territorial spatial planning, municipal engineering construction, comprehensive ecological restoration, and geological disaster prevention. Their data accuracy, update timeliness, and content completeness directly affect the scientific rigor of engineering design and management decision-making. With the accelerated pace of urbanization in China and the increasing stringency of natural resource management, various sectors have imposed more rigorous demands on topographic mapping products in terms of accuracy standards, update frequency, and data dimensionality. Traditional surveying methods, which rely on manual field operations for point-by-point coordinate collection, encounter considerable difficulties in complex terrains such as mountainous areas, dense forests, water bodies, and steep slopes—not only due to high fieldwork difficulty and significant safety risks for personnel, but also because they often produce extensive data gaps. Moreover, the prolonged mapping cycle makes it difficult to achieve dynamic updates of topographic and geomorphic information.

Unmanned aerial vehicle (UAV) photogrammetry enables rapid acquisition of high-resolution imagery of the survey area without being constrained by complex terrain conditions. When coupled with the powerful spatial analysis capabilities of geographic information system (GIS), it facilitates an integrated workflow encompassing image correction, data interpretation, three-dimensional terrain modeling, standardized map output, and spatial data storage management, thereby fundamentally addressing many shortcomings of conventional surveying approaches. Although UAV-GIS integrated surveying solutions have been widely adopted for large-scale digital topographic map production, practical project implementation still faces challenges in flight parameter configuration, ground control point (GCP) layout design, selection of data processing algorithms, and comprehensive quality control, which can lead to coordinate deviations, data redundancy, and missing feature elements in the final topographic maps. Given this context, further research and refinement of UAV-GIS collaborative digital topographic mapping protocols—along with the standardization of both field acquisition and indoor processing procedures—are of significant engineering value for improving the overall quality of

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surveying products.

2. Core Technical Principles of UAV-GIS Integrated Mapping

2.1 Technical Principles of UAV Photogrammetry

UAV photogrammetry primarily employs multi-rotor or fixed-wing light UAVs as operational platforms, equipped with high-resolution imaging cameras, real-time kinematic (RTK) high-precision positioning modules, and inertial measurement units. Following pre-programmed flight routes, the system automatically performs comprehensive, gap-free aerial image acquisition over the survey area [1]. During operation, sequential images with adequate forward and side overlap are captured. Combined with aerial triangulation techniques for computing image exterior orientation elements, massive feature points are accurately matched to generate high-density 3D point cloud data. This process yields digital surface models and digital elevation models, from which core geographic information—including terrain elevation, feature coordinates, and overall landform morphology—is precisely extracted, providing a complete and reliable foundational dataset for subsequent digital topographic map production. Compared with traditional manual surveying, UAV photogrammetry enables large-scale, non-contact intelligent data collection, effectively circumventing operational limitations imposed by complex terrains and significantly enhancing overall fieldwork efficiency.

2.2 Technical Principles of GIS Application

The core competency of GIS technology lies in its integrated spatial data processing and comprehensive analysis capabilities. It systematically processes multi-source data generated from UAV surveys—including raw imagery, 3D point clouds, and elevation models—through preprocessing, error correction, feature classification, and vectorization. GIS platforms can uniformly execute coordinate system conversion, seamless image mosaicking, systematic error correction, automatic feature extraction, and topological relationship verification. These processes convert massive, fragmented, unstructured surveying data into standardized, logically consistent geoinformation datasets. Concurrently, built-in spatial databases enable long-term storage, dynamic updates, rapid retrieval, and multi-layer overlay analysis of topographic data, with batch output of digital line graphs and layered thematic maps that conform to industry standards. This ensures both data logic and cartographic specifications are met, thereby guaranteeing the standardization and engineering applicability of mapping products.

2.3 Collaborative Mapping Logic of UAV and GIS

Within the integrated collaborative mapping framework, UAVs primarily undertake field data acquisition, effectively overcoming the efficiency bottlenecks and terrain constraints inherent in traditional surveying. GIS technology, in turn, focuses on refined indoor data processing and standardized map production, resolving issues such as raw data redundancy, uneven accuracy, and labor-intensive manual cartography. The complementary strengths of the two technologies form a closed-loop operation system characterized by "efficient field acquisition, refined indoor processing, and intelligent output." This enables automated generation of standardized digital topographic maps from raw aerial imagery, fully satisfying the high-precision mapping requirements for large-scale topographic maps at scales ranging from 1:500 to 1:2000 [2].

3. Standard Workflow for UAV-GIS Digital Topographic Mapping

3.1 Preliminary Reconnaissance and Mission Planning

Prior to field operations, comprehensive reconnaissance of the survey area is conducted to define its boundaries, topographic and geomorphic characteristics, vegetation cover, building distribution, and airspace restrictions, while identifying potential obstacles such as high-voltage power lines and tall structures. Based on the required mapping accuracy, GIS software is used to delineate survey boundaries and plan flight routes, altitude, forward overlap, and side overlap—typically setting forward overlap above 80% and side overlap above 75% to ensure complete image coverage without gaps or omissions. Additionally, a GCP layout plan is formulated according to terrain complexity, prioritizing open, unobstructed, and stable locations to ensure data processing accuracy.

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3.2 GCP Layout and Field Aerial Photography

GCP are uniformly distributed following surveying specifications, with densification in areas of significant terrain relief, survey boundaries, and pronounced elevation differences. RTK high-precision measurement equipment is employed to acquire plane and elevation coordinates for each GCP, ensuring foundational control accuracy. After completing UAV system calibration and camera parameter configuration, automated route-based aerial photography commences. Throughout the operation, real-time monitoring of flight attitude, signal transmission, and image quality is maintained, with proactive obstacle avoidance. The acquired images must be clear, evenly exposed, and meet the designed overlap requirements. Upon completion, all imagery is thoroughly inspected for completeness; any defective areas—due to missed captures, blurring, or insufficient overlap—are promptly re-flown.

3.3 Indoor Data Processing and Model Construction

Field-acquired aerial imagery and GCP coordinate data are imported into professional photogrammetric processing software. Aerial triangulation algorithms are applied for image orientation, followed by seamless mosaicking, lens distortion correction, and global color balancing to generate a high-density 3D point cloud of the survey area. Intelligent point cloud filtering algorithms are then employed to automatically remove noise points from vegetation, ground debris, and other interfering features, accurately retaining valid point cloud data that reflects true terrain morphology. Subsequently, high-precision digital elevation models and digital surface models are constructed, faithfully representing the overall terrain relief and spatial distribution of landforms in the survey area.

3.4 GIS Mapping and Product Refinement

The constructed high-precision terrain model data are imported into a GIS platform for systematic vectorization and mapping. Key topographic and planimetric elements—including contours, elevation control points, drainage networks, transportation routes, vegetation coverage, and building structures—are accurately extracted. Utilizing robust GIS topological analysis tools, common cartographic issues such as line overlaps, node discontinuities, and feature misalignments are batch-corrected. A unified coordinate system and vertical datum are applied throughout, and topographic elements are systematically organized by layer and category. Map annotations, legends, and scale parameters are comprehensively refined to ensure completeness and compliance. Finally, accuracy verification is performed against field-measured control points, with targeted corrections for data deviations and systematic errors, yielding standardized digital topographic maps that meet industry specifications and accuracy requirements.

4. Major Challenges in Current UAV-GIS Mapping Operations

4.1 Insufficient Accuracy Control in Field Operations

In some cases, improper flight route design, inadequate overlap settings, sparse or obstructed GCP placement, and other operational deficiencies result in suboptimal image matching accuracy and elevated aerial triangulation errors. Furthermore, forced operations under adverse weather conditions—strong winds, haze, backlighting, etc.—can cause image blurring and distortion, directly compromising terrain elevation data accuracy and leading to distorted contour lines and excessive elevation deviations.

4.2 Deficiencies in Indoor Data Processing Standardization

During indoor processing, improper tuning of point cloud filtering parameters can produce two types of quality issues: overly aggressive filtering thresholds may remove micro-topographic details such as gullies and terraces, while insufficient filtering fails to adequately eliminate noise from vegetation and debris, leaving interfering points. In the subsequent GIS vectorization stage, common problems include incomplete feature extraction, disordered layer categorization, and unresolved topological inconsistencies, resulting in missing content and non-compliant spatial logic in the final maps. Moreover, many operators rely on default software parameters without conducting site-specific calibration or accuracy verification, making the processing unsuitable for complex terrains such as mountains and woodlands, further degrading overall map quality.

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4.3 Inadequate Data Fusion and Update Mechanisms

UAV-derived raw data are diverse in type and often poorly compatible with GIS platforms in terms of format. During format conversion and data import/export, geographic information loss and degradation of coordinate/elevation accuracy frequently occur. In addition, most conventional surveying projects adopt a one-time acquisition and single-cycle mapping approach, lacking an institutionalized dynamic update mechanism. As a result, terrain changes induced by engineering construction or geomorphic evolution are not captured in a timely manner, compromising the currency of topographic maps and limiting their utility for dynamic monitoring in natural resource management and engineering applications.

5. Optimization Strategies for UAV-GIS Digital Topographic Mapping

5.1 Standardizing Field Workflows and Enhancing Raw Data Accuracy

It is essential for the industry to establish standardized field operation protocols. Practitioners should tailor flight parameters to specific terrain characteristics. They should adopt conventional parallel routes for flat areas. They should employ cross-flight routes with increased image overlap for complex regions such as mountains and ravines. Managers must strictly enforce GCP layout standards. Technicians should ensure uniform GCP distribution across the entire survey area. They should densify control points in zones with complex terrain. They must guarantee unobstructed sight lines and precise coordinate acquisition for every control point. Operators should carefully select appropriate weather windows for field operations. They should avoid adverse conditions such as strong winds, dense haze, and strong backlighting. These precautions are critical for ensuring optimal aerial image quality. Immediately after each field mission, technicians should verify the completeness and clarity of all acquired imagery. They must prevent any defective or substandard data from entering the subsequent indoor processing workflow. These measures are effective for controlling mapping accuracy at the very source of data acquisition [3].

5.2 Optimizing Indoor Processing Algorithms and Improving Cartographic Standardization

It is necessary for technicians to adjust point cloud filtering and aerial triangulation parameters according to the specific terrain features of each survey area. They should apply enhanced noise filtering in densely vegetated regions. They should reduce filtering intensity in micro-topographic zones, such as gully slopes and terrace edges, to preserve genuine terrain details. The industry should adopt standardized GIS mapping workflows. Technicians should perform layer-based vectorization of terrain elements in strict compliance with national surveying and mapping standards. They should systematically inspect contour line smoothness, elevation point density, and feature completeness. They should utilize GIS topological checking tools to automatically identify and correct line errors, polygon overlaps, and attribute omissions. The industry should unify the surveying datum and data format specifications across all projects. This unification facilitates seamless integration between UAV-acquired data and GIS platforms. This integration, in turn, improves both the standardization and positional accuracy of the final topographic maps.

5.3 Establishing Dynamic Update Systems and Strengthening Long-term Data Management

It is advisable for the industry to leverage GIS spatial databases for constructing a dynamic terrain information management platform. Managers should support this platform with a routine and institutionalized topographic map update mechanism. For areas that undergo frequent changes—such as active engineering construction zones, geological hazard sites, and ecological restoration regions—managers should organize periodic UAV re-survey missions. These re-surveys enable the timely capture of terrain modification data. Technicians should then replace outdated historical records in the database with the newly acquired information. Concurrently, it is important for developers to optimize multi-source data conversion algorithms. The industry should standardize storage formats across all types of surveying data. These measures are effective for reducing accuracy losses that commonly occur during data transfer and format conversion. This integrated system enables unified management of terrain data storage, rapid retrieval, dynamic updating, and cross-departmental sharing. This approach fully realizes the long-term reuse value of surveying products.

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5.4 Strengthening Personnel Training and Building Multidisciplinary Technical Teams

It is necessary for organizations to conduct regular and systematic training programs in UAV photogrammetry, GIS data processing, and topographic mapping standards. These training sessions should place special emphasis on error control, parameter optimization, and problem-diagnosis skills. Management should establish a three-tier quality control mechanism for the entire project lifecycle. This mechanism should include pre-employment competency assessment, in-process quality inspection during operations, and final acceptance review of deliverables. This system ensures that all operational procedures comply with established standards. Organizations should foster comprehensive technical competencies among their personnel. Each team member should master the full skill chain covering "field aerial surveying + indoor mapping + product verification." This training strategy eliminates single-skill bottlenecks within the team. This approach enhances the overall performance of the technical team and guarantees consistent quality of mapping products.

5.5 Adapting to Scenario-specific Applications and Expanding Technical Scope

It is important for practitioners to customize operational strategies according to the distinct mapping requirements of different application sectors. Territorial planning surveys should prioritize the completeness of all topographic and planimetric elements. Engineering construction surveys should emphasize localized high-precision elevation data at critical infrastructure locations. Emergency mapping operations should focus on rapid map production and real-time dynamic monitoring of disaster-affected areas. The industry should fully exploit UAV maneuverability and GIS spatial analysis capabilities. Practitioners should extend the application scope beyond basic topographic mapping. These extended applications include earthwork volume calculation, slope gradient analysis, terrain deformation monitoring over time, and natural resource inventory surveys. These value-added applications significantly enhance the comprehensive utility of the UAV-GIS technical framework [4].

6. Engineering Application Case Study

A 1:1000 digital topographic mapping project in a township is presented as a practical case. The survey area comprises diverse land cover types—mountains, farmlands, and residential zones—with significant overall relief and pronounced elevation variations. Given the complex terrain, traditional manual surveying would entail substantial fieldwork difficulty, heavy labor intensity, and an extended production cycle, making it challenging to meet project requirements efficiently. Accordingly, this project employed a “DJI Phantom 4 RTK UAV” for full-area aerial photography. During the preparatory phase, GIS software was used for intelligent flight route planning with complete coverage, and strict overlap settings of 85% forward and 80% side overlap were applied. A total of 32 GCPs were uniformly distributed based on terrain conditions to ensure data completeness and accuracy. Following field acquisition, professional photogrammetric software was used to construct a realistic 3D terrain model, which was then imported into a GIS platform for systematic vectorization, feature refinement, and topological correction. The final standardized 1:1000 digital topographic map was produced. Accuracy verification confirmed that both plane and elevation errors fully complied with national 1:1000 topographic mapping standards. Compared with conventional manual methods, the UAV-GIS collaborative approach reduced the mapping cycle by over 60%, significantly lowering labor and time costs, and proved highly suitable for complex terrains combining mountainous areas and residential zones. This engineering practice demonstrates that the optimized UAV-GIS collaborative mapping strategy substantially improves both the accuracy and efficiency of large-scale topographic mapping, exhibiting strong practicality and adaptability, with considerable potential for broader application in similar complex-terrain surveying projects.

7. Conclusion

The deep integration of UAV photogrammetry and GIS technology has reshaped the traditional digital topographic mapping production system. With outstanding advantages including high operational efficiency, accurate products, flexible deployment, and low costs, this integrated approach has become a mainstream solution in modern surveying engineering. To address the prominent issues of inadequate accuracy control, low workflow standardization, and untimely geoinformation updates in current practice, the optimization strategies proposed—standardizing field procedures, refining indoor processing algorithms, improving data management systems, enhancing personnel competencies, and

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adapting to scenario-specific applications—can effectively improve the quality of digital topographic mapping products and ensure their accuracy, timeliness, and compliance. With ongoing advancements in UAV payload sensors, 3D reality modeling algorithms, and big-data GIS platforms, UAV-GIS integrated surveying technology is poised to evolve toward fully automated, ultra-high-precision, real-time dynamic, and multi-dimensional visualization capabilities. This will progressively enable integrated operations encompassing autonomous flight, intelligent feature interpretation, on-site rapid mapping, and dynamic terrain monitoring. The technical framework will further deepen its application in natural resource management, smart city development, geological disaster early warning and mitigation, and ecological environment restoration, thereby establishing a solid technological foundation for the digital transformation and high-quality sustainable development of the geoinformation industry.

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