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Development and Application of an Automated Full-Process Framework for Unauthorized Land-Use Parcel Verification Driven by a UAV Hangar System: A Case Study in Shanghai, China

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Abstract

Traditional manual and satellite monitoring for unauthorized land-use parcels face limitations in timeliness, coverage, and efficiency. To address these challenges, this study proposes an automated full-process verification framework driven by an unmanned aerial vehicle (UAV) hangar system. Operating on a three-tier "cloud-edge-terminal" architecture, the framework seamlessly integrates five sequential links: intelligent scheduling, automatic data acquisition, real-time transmission, semantic interpretation, and result dissemination. Its core technical stack features direct georeferencing, parcel segmentation, and adaptive path planning. Specifically, a dynamic routing strategy combining an improved A* algorithm for local obstacle avoidance with Ant Colony Optimization (ACO) for global multi-target planning is introduced to accelerate inspection response speeds, achieving a closed-loop automation of parcel detection, verification, and evidence collection.

To validate technical feasibility and adaptability, a field experiment was conducted in Shanghai, China, utilizing 6 UAV hangar base stations to inspect 120 target parcels (including 32 slender-shaped ones). Experimental results demonstrate that the system-generated routes achieved 100% coverage completeness—fully capturing all parcel boundaries within the camera's effective field of view—while minimizing redundant traversal. Furthermore, the framework reduced manual operation time by 75% compared to traditional manual planning methods, requiring human intervention only for final result validation. Parametric configuration also enables rapid system adaptation to diverse regulatory scenarios, providing an efficient technical paradigm for targeted supervision in territorial governance.

1. Introduction

1.1 Background

Unauthorized land-use parcels (including unauthorized land occupation, unapproved construction, ecological disturbance, and illegal mining, etc.) serve as the core regulatory targets for territorial and spatial use control and ecological protection. They directly pose threats to the order of territorial and spatial development, the security of the ecological environment, and the protection of basic farmland (a critical safeguard for food security, defined as "cultivated land protection red line" in China's land governance system). Taking Shanghai, China as an example, its urbanization rate had reached 89.3% by 2024 (per the 2024 Shanghai Statistical Communique). The growing contradiction between urban expansion and resource development has further intensified, rendering traditional manual verification methods for unauthorized land-use parcels inadequate in meeting the demands for targeted and rapid response. Consequently, there is an urgent need to develop an efficient, high-precision automated verification technology system—one that provides technical support for the "early detection, early prevention, and early handling" of illegal and irregular activities in territorial and spatial governance.

1.2 Research Status

Unauthorized land-use parcel verification has undergone three technical stages of development; however, key limitations persist incrementally, failing to meet the demands of modern territorial and spatial supervision:

Satellite remote sensing monitoring enables large-scale coverage for preliminary screening but is constrained by inherent limitations: limited spatial resolution (e.g., Gaofen-2, with a 2 m resolution, cannot identify parcels smaller than 100 m²), long revisit cycles (e.g., Landsat-8 has a 16-day revisit interval), and frequent cloud-fog interference typical in coastal megacities like Shanghai. In local enforcement practice, high-resolution satellites (e.g., Gaofen-2) are often used as baselines, but their effectiveness is heavily constrained by these weather conditions. To address the imprecision of satellite data, manual on-site verification achieves high accuracy but is extremely inefficient. Conventional UAV-based verification improves efficiency with centimetre-level resolution (5–10 cm) and flexible deployment (within a 5–10 km radius); however, it remains semi-automated, relying on manual point annotation, on-site task scheduling, offline image interpretation, and evidence compilation. Zhang et al. (2020) pointed out that although UAV remote sensing has been initially applied in the monitoring of unauthorized parcels in territorial space, this semi-automated model still cannot meet the needs of large-scale and high-frequency verification, which is consistent with the limitations of traditional methods observed in this study. As a result, large-scale or periodic verification is inefficient (with a maximum of 2 inspections per area per month), failing to address "scattered and rapidly expanding" unauthorized parcels. The core challenge of "incomplete automation and underutilized technical potential" thus remains unresolved.

In summary, current verification technologies face three interrelated challenges: low timeliness and high omission rates in preliminary screening, high costs and poor standardization in precise verification, and insufficient automation in technical advancement. These issues collectively hinder the achievement of targeted, efficient, and regular territorial and spatial supervision.

1.3 Research Objectives and Core Innovations

This study aims to develop an automated full-process framework for unauthorized land-use parcel verification driven by a UAV hangar system, with the core goals of "unattended operation, closed-loop workflow, and rapid response". It will quantitatively evaluate the system's performance from three dimensions: verification accuracy, response timeliness, and adaptability to manual verification scenarios, thereby providing a technical paradigm for data-driven targeted supervision and efficient handling of illegal and irregular activities in territorial and spatial governance.

The core innovations of this study are manifested in three aspects: First, system innovation – an integrated automated system encompassing "UAV hangar – UAV platform – edge computing – cloud-based verification platform" is established to support 24/7 unattended verification. This system shortens the full-process cycle of unauthorized land-use parcel "detection–verification–evidence collection" from the traditional 15 days (manual verification) to 48 hours, significantly improving the efficiency of territorial and spatial supervision. Second, system-level algorithmic integration–a dynamic route optimization strategy (improved A* combined with ant colony algorithm) is proposed, which integrates multi-UAV swarm coordination, terrain constraints, and unauthorized parcel distribution characteristics. This algorithm optimizes path planning for scattered and concealed unauthorized parcels, effectively reducing the flight interruption rate and enhancing the verification response speed – a key technical breakthrough aligned with ISPRS's focus on UAV-based spatial information acquisition efficiency. Third, application innovation–targeted application and verification are conducted in agricultural-related areas of Shanghai, China (a typical megacity). Li et al. (2023) had previously attempted to use UAV hangar systems to carry out automated verification of unauthorized agricultural land use in Shanghai, but there was room for optimization in two key links: 'dynamic path adjustment' and 'multi-model collaborative recognition', which are also among the core breakthrough directions of this study.

2. Experimental Area

The study area is Shanghai, China—a megacity characterized by high-intensity land use and distinct urban-rural integration features. Within this region, unauthorized land-use parcels exhibit three typical characteristics: widespread distribution, diverse types, and regional differentiation. Land use patterns are highly interlaced, and regulatory boundaries remain complex, posing challenges for traditional verification methods. Key high-incidence areas of unauthorized land-use parcels are concentrated in three categories:

Suburban urban-rural fringes and "villages within urban areas" (a unique spatial unit in rapidly urbanizing regions), where the primary issues include non-compliant expansion of rural residential plots and industrial unauthorized land use;

Transition zones between basic farmland and construction land in the outer suburbs, with prominent problems of unauthorized land occupation (specifically, conversion of basic farmland to construction land) and unapproved expansion of facility agriculture;

Peripheral areas of ecological protection boundaries (e.g., Dianshan Lake, Yangtze River coastline), where ecological disturbance-type unauthorized parcels are prevalent—such as deforestation and waste dumping in water-adjacent zones.

The entire study area exhibits significant land fragmentation. Small and medium-sized unauthorized land-use parcels (with individual areas mostly less than 500 m²) account for over 60% of the total, which aligns closely with the distribution pattern of unauthorized parcels in global megacities. This spatial and typological diversity enables comprehensive testing of the system's adaptability in verifying unauthorized parcels across different types and regional contexts. Covering major violation categories—including unauthorized land occupation, unapproved construction, and ecological disturbance—Shanghai serves as an ideal site for technical verification of unauthorized land-use parcel detection, with strong practical representativeness for similar high-intensity land-use regions worldwide.

3. Automated Monitoring Framework of the UAV Hangar System

3.1 Overall System Architecture

The system adopts a three-tier "cloud-edge-terminal" architecture, integrating five core modules—intelligent scheduling, automated data acquisition, real-time transmission, semantic interpretation, and result dissemination—to establish a closed-loop automated workflow (**Figure 1**). for unauthorized land-use parcel "detection – verification – evidence collection – disposal".

The "terminal" layer comprises UAV hangars and UAV platforms, which are responsible for precise evidence collection and on-site data acquisition at locations with unauthorized land-use activities. The "edge" layer consists of edge computing nodes embedded in the UAV hangars, undertaking real-time data preprocessing (e.g., preliminary geometric correction of aerial imagery) and preliminary validation of the evidence chain to ensure data reliability before cloud transmission. The "cloud" layer is a cloud-based platform dedicated to unauthorized land-use parcel verification, which manages task scheduling, AI-powered semantic interpretation, and verification result management. This integrated architecture enables a full-area coverage model combining "fixed hangar-based deployment + mobile UAV inspections", aligning with the demand for continuous territorial and spatial supervision.

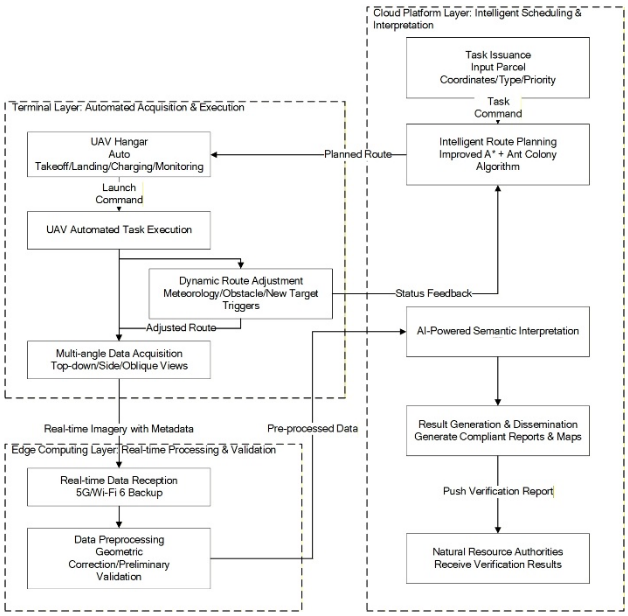

Figure 1. The automated full-process framework for unauthorized land-use parcel verification driven by a UAV hangar system.

3.1.1 Hardware Composition

UAV Hangar: A highly integrated, standardized outdoor UAV docking station (e.g., DJI Dock series, characterized by a compact design with a weight of ≤ 105 kg and an IP55 protection rating) is deployed. It is integrated with a suite of functional components, including an automatic takeoff-and-landing platform, a fast-charging system, environmental monitoring sensors, and security modules. Specifically, equipped with a TEC (Thermoelectric Cooling) air-conditioning system, it can fast-charge the UAV from 10% to 90% within 25-30 minutes, seamlessly supporting high-frequency continuous operations without the need for complex mechanical battery swapping. The integrated environmental sensors monitor key meteorological parameters (temperature, humidity, wind speed, and rainfall) in real time to ensure flight safety, while the security modules include wide-angle surveillance cameras. This hangar enables all-weather UAV deployment within a temperature range of -25 °C to 45 °C, robustly addressing the demand for uninterrupted, unattended territorial supervision.

Cloud Platform: The platform is deployed on Alibaba Cloud servers with specified hardware configurations (8-core CPU, 16 GB memory, and 5 TB OSS storage). Its core functionalities include supporting multi-user concurrent access, implementing intelligent task scheduling (e.g., assigning UAV inspection tasks based on parcel priority), and enabling result visualization (e.g., spatial overlay display of unauthorized land-use parcels and verification images). This cloud-based architecture provides a centralized management interface for the entire automated verification workflow, aligning with ISPRS's focus on integrating cloud computing with spatial information processing.

To provide a clear overview of the operational capabilities and to address the stringent requirements for high-precision georeferencing, the detailed hardware specifications of the UAV hangar system are summarized in Table 1.

Table 1. System Hardware and Technical Specifications

Component	Key Specifications
UAV Platform	DJI Enterprise Series (e.g., Matrice 30T/3TD). Max flight time: ~40 mins; Max wind resistance: 12 m/s; IP55 rating.
Camera Payload	Multi-sensor integration: (1) Wide camera: 12 MP (Equivalent focal length: 24 mm). (2) Zoom camera: 48 MP. (3) Laser Rangefinder & Thermal sensor (for detecting concealed targets).
GNSS/IMU System	RTK Enabled (Network RTK / D-RTK Mobile Station integrated). Horizontal Positional Accuracy: 1 cm + 1 ppm (RMS); Vertical Positional Accuracy: 1.5 cm + 1 ppm (RMS). (Provides centimeter-level high-precision direct georeferencing).
UAV Hangar	DJI Dock Series. TEC fast-charging (10-90% in 25 mins); Built-in weather station and ultra-wide-angle security camera; Operating temperature: -25 °C to 45 °C.
Edge Compute Node	Embedded industrial computing unit (for real-time video streaming, preliminary data preprocessing, and reliable transmission control).
Network & Data Link	Dual-mode: 5G government dedicated network + WiFi 6. Average transmission latency: ≤ 200 ms (measured under optimal line-of-sight and 5G coverage conditions).

3.1.2 Data Flow and Control Process

The data flow and control process of the system follows a standardized and automated workflow, ensuring the efficient execution of unauthorized land-use parcel verification tasks. In the task issuance phase, users import clues of unauthorized land-use parcels—including key information such as geographic coordinates, violation types, and priority levels—through the cloud platform. Meanwhile, they specify requirements for verification timeliness and evidence collection accuracy, which serve as critical parameters to guide subsequent UAV operation planning and execution. For the route planning link, the scheduling module integrates three core constraint factors to generate the optimal evidence collection route: real-time meteorological conditions (with thresholds set as wind speed ≤ 5 m/s and precipitation probability ≤ 20%, designed to ensure flight safety and the quality of collected image data), terrain characteristics (e.g., avoiding obstacles like high-voltage lines or water bodies that may affect flight safety), and the distribution density of unauthorized land-use parcels. This multi-factor integration approach not only guarantees the efficiency of the planned route but also ensures the completeness of coverage for target verification parcels.

In the automatic execution stage, the system dispatches the UAV for takeoff, and the UAV performs multi-angle image acquisition (including top-down and side views) of sites with unauthorized activities along the pre-planned route. For concealed unauthorized parcels—such as those obscured by vegetation or buildings that may lead to incomplete image capture—the UAV can automatically adjust its flight altitude and camera angle to optimize the evidence capture effect, effectively addressing the challenge of incomplete data collection for hidden violations. During real-time transmission, the system adopts a dual-mode transmission mechanism of "5G + WiFi 6 backup," which enables the UAV to transmit aerial images tagged with metadata (e.g., shooting time, geographic location, and camera parameters) to edge computing nodes in real time. Key performance indicators of this transmission system meet high standards: the transmission latency is ≤ 200 ms, and the packet loss rate is < 0.1%, ensuring timely and reliable data transfer to support subsequent semantic interpretation of images. Finally, in the result dissemination phase, the system automatically pushes verification task notifications to natural resource authorities. These notifications include comprehensive core information, such as the geographic coordinates of unauthorized land-use parcels, metadata-tagged aerial images, preliminary violation identification results, and targeted disposal recommendations.

This output fully complies with the evidence submission requirements for satellite remote sensing-assisted verification, effectively bridging the gap between technical verification of unauthorized parcels and practical disposal actions.

3.2 Intelligent Route Planning and Dynamic Adjustment Module

Focusing on the core characteristics of unauthorized land-use parcels—"scattered distribution, strong concealment, and stringent evidence collection requirements"—the route planning module constructs a two-stage optimization model consisting of "static planning and dynamic adjustment". This model is specifically designed to balance two critical objectives in unauthorized parcel verification: rapid response to priority tasks and high-quality evidence collection, addressing the technical trade-off between efficiency and data reliability in UAV-based inspection.

3.2.1 Static Route Planning

To address the complex multi-target routing problem, this study combines the improved A* algorithm with Ant Colony Optimization (ACO). Specifically, the improved A* algorithm is first employed to calculate the collision-free shortest path cost matrix between any two unauthorized parcels (accounting for local obstacles). Based on this cost matrix, the ant colony algorithm can effectively solve the optimization problem of multi-target access order through its 'pheromone update' mechanism (Dorigo and Stützle, 2019). Based on this, this study integrates the ant colony algorithm into path planning and adjusts the pheromone concentration through a 'local update + global update' strategy to adapt to the scattered distribution characteristics of unauthorized parcels:

g(n): The actual cost from the start point to node n, including path length cost and priority weight (the weight of urgent illegal sites is increased by 50%).

h(n): The heuristic function from node n to the end point, including evidence collection accuracy cost and obstacle avoidance cost (avoiding obstacles such as urban village buildings, rivers, and high-voltage power lines with a safe distance > 30m).

On this basis, the ant colony algorithm is incorporated to optimize the access order of illegal sites. The pheromone concentration is adjusted through a "local update + global update" strategy:

Local Update: After an ant traverses a path, the pheromone concentration is updated as:

$$\tau_{ij}(t+1) = (1-\rho_l)\tau_{ij}(t) + \rho_l\tau_0$$

Where ρ_l denotes the local evaporation coefficient, an τ_0 is the initial pheromone concentration.

Global Update: After each iteration, the pheromone of the optimal path is enhanced, updated as:

$$\tau_{ij}(t+1) = \left(1-\rho_g\right)\tau_{ij}(t) + \rho_l\Delta\tau_{ij}$$

Where ρ_g is the global evaporation coefficient, and $\Delta\tau_{ij}$ represents the pheromone increment.

Key performance parameters of the statically planned route include: the average number of shooting angles per unauthorized site exceeds 3 (ensuring comprehensive evidence capture), the flight time per inspection area is less than 30 minutes (meeting urgent verification timeliness requirements), and the coverage rate of unauthorized sites reaches 100% (avoiding omissions).

3.2.2 Dynamic Route Adjustment

During UAV flight, the system triggers multi-dimensional dynamic route adjustments based on real-time data transmitted by the UAV, ensuring adaptability to unexpected scenarios and maintaining verification quality:

Meteorological Trigger: When real-time wind speed exceeds 10 m/s (posing risks to flight stability) or visibility drops below 1 km (compromising image clarity), the flight is immediately suspended, and the UAV returns to the hangar. This measure ensures the collected evidence meets the definition standards for verification.

Obstacle and New Parcel Trigger: Upon detecting unmarked obstacles (e.g., temporary soil piles, newly constructed structures not included in pre-flight terrain data), the UAV automatically detours with a detour radius ⩽ twice the obstacle height (preventing collisions while avoiding missing target parcels). If new unauthorized sites are identified during flight, the route is adjusted to approach and capture supplementary images, enriching the evidence chain for subsequent verification and disposal.

Priority Trigger: When clues of urgent unauthorized parcels are received (e.g., illegal construction in key ecological zones), the system interrupts ongoing regular verification tasks, re-plans the route based on the "nearest response" principle, and ensures the UAV arrives at the new verification site within 30 minutes—addressing the timeliness requirement for emergency disposal.

3.3 Unauthorized Land-Use Parcel Verification and Processing

To standardize verification evidence collection, enhance data processing efficiency, and facilitate the application of verification results, the system builds an integrated framework for UAV aerial image processing. This framework directly addresses the core needs of "evidence fixation, data tracing, and result output" in unauthorized land-use parcel verification, with key functionalities outlined as follows.

3.3.1 Automated Geometric Correction of Aerial Images

To meet the spatial precision requirements of verification, this function automates the geometric accuracy optimization of UAV aerial images. The system first extracts key metadata from the UAV and camera, including GPS coordinates of the shooting location, flight attitude parameters (pitch, yaw, roll), and camera intrinsic parameters (focal length, sensor size). The UAV image geometric correction method proposed by Wang et al. (2021) points out that the correction strategy integrating flight attitude and camera internal parameters can significantly reduce the tilt distortion error, which provides direct technical reference for the design of the system correction process in this study. It then processes the images using WGS84 geographic coordinates as the reference system, correcting geometric distortions caused by flight attitude fluctuations (e.g., tilt-induced image skewing). The output is standardized TIFF images with preserved geographic information. Assisted by the UAV's onboard RTK module, the absolute spatial positioning error of the georeferenced images achieved a Root Mean Square Error (RMSE) of approximately 0.15 m horizontally, validated by independent RTK ground checkpoints. These comply with verification evidence accuracy standards while minimizing manual intervention and reducing human-induced errors.

3.3.2 Vector Overlay and Attribute Association of Unauthorized Parcels

To support traceability of parcel information, this function enables precise matching between unauthorized parcel vector data and geometrically corrected aerial images. It imports mainstream vector formats (e.g., Shapefile) and automatically overlays parcel boundaries on the images with high-visibility rendering (e.g., bold red lines) for clear identification. Additionally, the system extracts core parcel attributes (unique identifier, administrative jurisdiction, violation type) and labels them at the parcel centroid—realizing a closed-loop association of "image-parcel-attribute" without manual operation. This enhances the targeting and efficiency of verification by allowing relevant personnel to quickly link spatial images with attribute information.

3.3.3 Batch Automated Processing and Scenario Adaptation

Catering to large-scale verification needs (e.g., multi-area, high-volume parcel inspections), the system supports automated batch processing of aerial images in multiple formats (JPG/JPEG). It adapts to different shooting angles: images that meet pre-defined standards (e.g., tilt angle < 5°) are directly standardized, while severely distorted images (e.g., tilt angle > 10°) undergo full geometric correction. The framework is also compatible with image data collected under complex weather conditions (e.g., mild haze), and allows parameterized configuration of processing parameters (e.g., geometric correction precision, image compression ratio) for diverse scenarios (urban-rural fringes, ecological protection zones). This enables unattended batch operations, significantly saving manual processing time.

3.3.4 Standardized Verification Result Output

Aligning with national and local verification evidentiary standards, the system provides two core types of output:

Georeferenced TIFF images: These retain precise spatial coordinates, supporting accurate verification tasks such as parcel area measurement and boundary confirmation.

Visualized verification maps: These integrate overlaid parcel boundaries, attribute labels, and optimized timestamp watermarks (positioned to avoid obscuring key violation details, e.g., unauthorized construction structures).

All output formats comply with the import standards of natural resource supervision platforms, enabling seamless data transfer between the verification system and practical disposal workflows—accelerating the transition from technical verification to on-site disposal action.

3.3.5 Intelligent Feature Recognition and Preliminary Violation Assessment

To further enhance the automation and accuracy of verification, the system includes extensible intelligent interpretation interfaces, supporting multi-model collaboration for preliminary violation screening:

Large Model Integration: Standardized application programming interfaces (APIs) support integration with mainstream visual large models (e.g., CNN-based image recognition models). Among them, the CNN-based image segmentation technology is centered on the U-Net network (Ronneberger et al., 2015), and its encoder-decoder structure can accurately extract the edge and contour features of unauthorized parcels, providing technical support for the subsequent identification of suspected violation clues.

Remote Sensing Model Adaptation: The system integrates lightweight, self-trained remote sensing models tailored to specific regions (e.g., Shanghai's urban-rural integration areas) and violation types (e.g., illegal conversion of farmland to construction land). These models perform feature classification and change detection (comparing current images with historical baseline data), delivering quantitative results such as violation probability distribution and matching degree with known illegal patterns.

Collaborative Process Optimization: Recognition results from large models and remote sensing models are matched with a pre-built violation rule base (incorporating land use planning data and verification standards). The system then generates preliminary conclusions, including suspected violation type, key evidence (e.g., location of unauthorized structures), and confidence level (e.g., 90% certainty for clear construction violations). Only cases with confidence levels ⩾ 85% require manual review, significantly reducing the workload of relevant verification personnel. Additionally, intelligent recognition results are linked with other system functions (e.g., vector overlay, result output) to automatically generate inspection reports—advancing the full-process intelligence of unauthorized parcel verification.

This streamlined verification and processing framework comprehensively enhances the efficiency, accuracy, and intelligence of unauthorized land-use parcel verification, from UAV image collection to the application of verification results.

4. Application and Experimental Verification (A Case Study of Shanghai)

4.1 Experimental Design and Verification Process

To accurately evaluate the system's practical effectiveness in verifying unauthorized land-use parcels within Shanghai's agricultural-related areas, this research focuses on the regional characteristics of the study area—concentrated basic farmland, dense facility agriculture, and agriculture-related violations as the dominant unauthorized types. The system was deployed in agricultural-related districts of Shanghai, including Pudong New Area, Songjiang, Jinshan, Qingpu, Fengxian, and Chongming, targeting high-frequency violations in these regions: unauthorized occupation of basic farmland (conversion to construction land), unapproved expansion of facility agriculture, and ecological disturbance around cultivated land (e.g., waste dumping, felling of farmland shelterbelts).

4.1.1 Task Sources and Verification Indicators

The verification tasks are precisely aligned with the verification needs of Shanghai's agricultural-related areas. They cover suspected agriculture-related unauthorized land-use parcels sourced from Shanghai's satellite remote sensing-assisted verification system and other official channels, ensuring that the experimental tasks closely match real-world regulatory priorities and target high-frequency violations in agricultural regions.

In line with Shanghai's agricultural-related verification assessment standards, key verification indicators are defined to comprehensively evaluate the system's practical performance. These indicators mainly include two core dimensions: verification timeliness and verification accuracy. Verification timeliness is measured by the response time for agriculture-related unauthorized clues (from task initiation to UAV deployment) and the evidence collection cycle (from UAV takeoff to the completion of real-time data transmission). Verification accuracy is assessed through the recognition accuracy of agriculture-related violation types (e.g., unauthorized conversion of basic farmland, unapproved expansion of facility agriculture) and the spatial positioning error of unauthorized parcels—both of which are critical to meeting the evidentiary standards of verification.

4.1.2 Verification Process

Automatic execution is tailored to Shanghai's agricultural-related verification timeliness requirements: urgent tasks must be completed within 3 hours, and regular tasks within 24 hours. To meet these standards, the hangar system integrates local terrain features—such as dense river networks, contiguous farmland blocks, and interlaced shelterbelts—with rural road constraint information (e.g., restricted access zones) to plan optimal evidence collection routes. At unauthorized sites, the system autonomously conducts multi-angle image acquisition: top-down shots for parcel area confirmation, side shots to measure the height of unauthorized structures, and oblique shots to capture concealed details (e.g., violations behind vegetation or buildings). All collected data are transmitted in real time via Shanghai's 5G government dedicated network, ensuring minimal latency in data transfer for subsequent processing.

Intelligent interpretation leverages a general image recognition model trained on agricultural scenarios to identify typical ground objects in Shanghai’s agricultural areas, including rice fields, vegetable plots, facility agriculture greenhouses, farmland shelterbelts, rural roads, and agriculture-related buildings. By analyzing these features, the model detects anomalies indicative of agriculture-related violations (e.g., structures in protected farmland or expanded greenhouses beyond approved boundaries). It then generates a preliminary verification report that incorporates localized attributes specific to Shanghai’s agricultural regions, such as the affiliated township, cultivated land classification (e.g., basic farmland vs. general agricultural land), In this experimental deployment, the U-Net-based preliminary screening module achieved an estimated precision of 88.5% and a recall of 92.1% for typical agriculture-related violations, effectively filtering out false alarms before manual review.

Targeted on-site verification streamlines efforts by focusing only on high-confidence cases (⩾85% certainty) identified by the intelligent system. Relevant verification personnel at municipal, district, and town levels in Shanghai's agricultural areas retrieve spatial planning data via Shanghai’s territorial space planning "unified map" (cultivated land protection special edition) to cross-reference parcel boundaries and land use designations. They verify the spatial accuracy of unauthorized parcels using RTK (Real-Time Kinematic) positioning technology, ensuring sub-meter precision in location confirmation, and ultimately confirm the violation status based on regulatory standards. This tiered verification process balances automation with human oversight, optimizing efficiency while maintaining verification rigor.

4.2 Analysis of Unauthorized Land-Use Parcel Verification Results in Shanghai’s Agricultural-Related Areas

Regarding operational robustness, out of the 50 automated UAV missions conducted during the test period, only 2 missions were interrupted and forced to return to the hangar triggered by sudden severe weather (e.g., wind speeds exceeding the 10 m/s safety threshold). This resulted in a high mission success rate of 96.0%, with no hardware losses or safety incidents, demonstrating the system's reliability in practical multi-site deployments.

Indicators	UAV Hangar System	Traditional manual verification methods	Improvement Rate
Response time for agriculture-related illegal clues	30 minutes	48 hours	99.0% reduction
Evidence collection cycle for key agricultural-related areas	15 minutes	3 hours	91.7% reduction
Evidence fixation cycle for agriculture-related violations	48 hours	30 days	93.3% reduction

Table 2. Comparison of Timeliness Between the System and Traditional manual verification methods s in Shanghai’s Agricultural-Related Areas

As illustrated in the Table 2, the system effectively addresses the core pain points of traditional manual verification methods in Shanghai’s agricultural-related areas—namely "slow response speed and low cross-district operation efficiency"—while resolving the practical dilemma posed by "extensive geographic coverage, contiguous cultivated land blocks, and scattered manual inspection resources". Notably, the evidence fixation cycle for agriculture-related violations is shortened from 30 days (traditional manual approach) to 48 hours, fully complying with the statutory timeliness requirement of "fixing evidence within 72 hours" specified in the Shanghai Land Illegal Case Investigation and Handling Procedures (Agriculture-Related Special Edition). This significant efficiency improvement directly curbs evasive behaviors among violators in Shanghai’s agricultural areas, such as "rush construction after crop harvest" and "night-time unauthorized construction", which often exploit the inherent lag of traditional manual verification.

5. Conclusions and Future Work

This study develops an automated full-process framework for unauthorized land-use parcel verification driven by a UAV hangar system, integrating five core technologies: intelligent scheduling, automated data collection, real-time transmission, AI-powered semantic interpretation, and compliant result dissemination. Continuous experimental verification was conducted in agricultural-related districts of Shanghai, China—including Pudong New Area, Songjiang, Jinshan, Qingpu, Fengxian, and Chongming. The main conclusions are as follows:

First, full-process automation of unauthorized land-use parcel verification in agricultural-related areas is realized. Through the three-tier "cloud-edge-terminal" architecture and localized adaptive optimization, the system enables 24/7 unattended closed-loop operation. A single verification task is completed within 1 hour, and the discovery cycle of agriculture-related unauthorized parcels is shortened to 48 hours—fully meeting the high-frequency, rapid-response, and high-compliance requirements of agricultural-related verification in Shanghai.

Future research will focus on deepening scenario adaptation and expanding application value, with three key directions: first, upgrading the hardware system to enhance resilience against extreme weather conditions (e.g., heavy rain, strong winds), enabling truly all-weather and round-the-clock monitoring of unauthorized parcels; second, optimizing the integrated deep learning model by incorporating local territorial space planning data and temporal change characteristics (e.g., seasonal agricultural activities), improving recognition accuracy for complex agriculture-related violations (e.g., partial conversion of farmland, concealed facility expansion); third, further integrating with Shanghai’s "Unified Network Governance Platform" and the "Yangtze River Delta Cultivated Land Protection Supervision Collaboration Platform". The application scope will be expanded to key towns and high-quality cultivated land protection zones in Shanghai’s agricultural-related districts, constructing an intelligent supervision network for agriculture-related violations that covers the entire city and radiates the Yangtze River Delta region. This research is expected to provide robust technical support for Shanghai to safeguard the basic farmland protection red line and promote the effective implementation of the rural revitalization strategy.

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