A Multi-Dimensional Digital Twin Framework for the Low-Altitude Economy

Yan Li, Chenming Ye, Wenxuan Shi, Wenqing Zhang, Yuyang Zhang, Teng Hu, Zhizhong Kang*

School of Land Science and Technology, China University of Geosciences (Beijing), Beijing, China – yanli.yny@cugb.edu.cn; yechenming@email.cugb.edu.cn; shiwenxuan@email.cugb.edu.cn; zhangwenqing@email.cugb.edu.cn; yuyond@ncut.edu.cn; huteng@cugb.edu.cn; zzkang@cugb.edu.cn
*Corresponding author

Keywords: Low-Altitude Economy, Digital Twin, Geospatial Infrastructure, Environmental Sensing, Interaction, Technology Readiness Level.

Abstract

The Low-Altitude Economy (LAE), driven by the widespread deployment of UAVs and eVTOL aircraft, demands a high-fidelity Digital Twin that extends far beyond static geographic representation. This study presents a critical review of 39 peer-reviewed papers to propose a three-layer mapping framework — Geospatial Infrastructure Layer, Environmental Sensing Layer, and Interaction Layer — and evaluates the Technology Readiness Level (TRL) of each sub-domain. The Geospatial Infrastructure Layer encompasses terrain models, ground facilities, airspace structures, and semantic navigation landmarks. The Environmental Sensing Layer covers electromagnetic modeling, target sensing and countermeasure, and micro-meteorological mapping. The Interaction Layer addresses network trust, data security, swarm coordination, and platform reliability. Our TRL assessment reveals that Environmental Sensing is the most mature layer (mean TRL 4.4, 8 field-validated papers), while cross-layer integration remains the weakest link (mean TRL 3.5, zero field-validated demonstrations). We identify standardization of low-altitude spatial data products, AI-enabled predictive mapping, crowdsourced Digital Twin updating, and closed-loop cross-layer integration as the four priority research directions.

1. Introduction

The Low-Altitude Economy (LAE) utilizes airspace generally below 1,000 m above ground level for commercial activities including transportation, logistics, and urban services (Jiang et al., 2024). China’s low-altitude airspace economy exceeded CNY 500 billion in 2023 and is projected to reach CNY 3.5 trillion by 2035 (Zhao et al., 2025). The European Union's U-Space initiative and the U.S. FAA's Advanced Air Mobility framework further underscore global momentum (Liu J. et al., 2025). The anticipated scale — millions of aircraft sharing low-altitude airspace — demands comprehensive environmental awareness and inter-system coordination far beyond what current systems provide.

Constructing a high-fidelity Digital Twin (Tao et al., 2019) is critical for safe and scalable Unmanned Traffic Management (UTM) (EUROCONTROL, 2023). However, current mapping approaches suffer from three limitations: (1) confinement to static geographic information, lacking dynamic physical fields such as electromagnetic quality and micro-meteorology (Jiang et al., 2024; Meng et al., 2024); (2) fragmented development of sensing technologies without a unifying spatial mapping framework (Wang Y. et al., 2025a; Li Z. et al., 2025); and (3) absence of systematic representations of how heterogeneous system entities — aircraft, network nodes, ground infrastructure, and regulatory bodies — interact, coordinate, and establish mutual trust (Li Y. et al., 2025; Hu et al., 2025).
This paper reviews 39 papers published primarily between 2024 and 2025, proposing a three-layer framework — Geospatial Infrastructure, Environmental Sensing, and Interaction — and provides the first systematic TRL assessment across all sub-domains. The contributions include: (1) a multi-dimensional mapping framework grounded in spatial information science, with three layers addressing where (geospatial), what is happening (sensing), and how entities collaborate (interaction); and (2) a quantitative TRL assessment revealing that cross-layer integration (mean TRL 3.5) is the most critical bottleneck, while individual Environmental Sensing technologies have reached field validation (mean TRL 4.4).

2. Framework and Review Methodology

2.1 Literature Screening

Table 1. Literature screening summary and classification by framework layer.

Stage	Count
Initial WOS retrieval	143
Excluded (unavailable + irrelevant)	104
Final retained	39
— Geospatial Infrastructure Layer	10
— Environmental Sensing Layer	19
— Interaction Layer	6
— Cross-layer	4

A structured search of the Web of Science Core Collection yielded 143 records. A three-step screening funnel was applied: (1) removal of 21 unavailable or pre-excluded records; (2) relevance screening excluding 82 papers on unrelated subjects (ecology, sports physiology), pure communication optimization without spatial outputs, or UAV hardware unrelated to environmental mapping; (3) classification of the remaining 39 papers into core papers (23, directly addressing surveying,

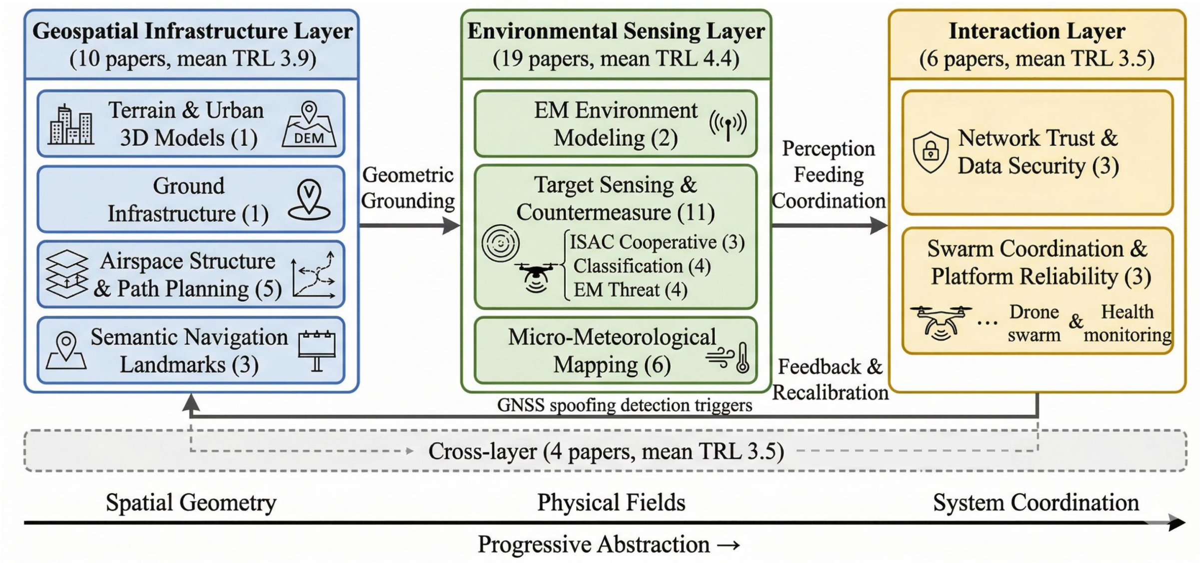

Figure 1. Three-Layer Digital Twin Mapping Framework for the Low-Altitude Economy. The framework comprises: (a) Geospatial Infrastructure Layer — terrain models, ground facilities, airspace structure, and semantic navigation landmarks; (b) Environmental Sensing Layer — electromagnetic modeling, target sensing and countermeasure, and micro-meteorological mapping; (c) Interaction Layer — network trust, data security, swarm coordination, and platform reliability. Arrows indicate inter-layer data dependencies. Paper counts annotated per sub-category.

remote sensing, or GIS topics) and bridge papers (16, providing essential technical foundations for specific framework layers). The screening results are summarized in Table 1.

The corpus is temporally concentrated: 29 papers (74%) were published in 2025, confirming that physical element mapping for the LAE is a rapidly emerging field. Simulation-based studies dominate (51%), with 11 papers (28%) achieving field-validated results (TRL $\geqslant$ 5). The search scope is limited to WOS with LAE-specific terminology; foundational works on Digital Twin theory (Tao et al., 2019), UTM standards (EUROCONTROL, 2023), SLAM (Campos et al., 2021), and CityGML (Biljecki et al., 2015) are cited as supplementary references but not included in the 39-paper systematic count.

2.2 Three-Layer Mapping Framework

The proposed framework (Figure 1) organizes the physical elements of the low-altitude environment into three progressively abstracted layers, following two design principles: progressive abstraction (from spatial geometry to physical fields to system-level coordination) and bidirectional dependency (layers form a closed-loop system with bottom-up data flow and top-down feedback).

Geospatial Infrastructure Layer provides the spatial foundation — both geometric and semantic — upon which all operations are built. It encompasses terrain and urban 3D models, ground infrastructure siting (vertiports, GA airports), airspace structure digitalization (vertical layering, geo-fences, route networks), and semantic navigation landmarks (pre-calibrated keypoint databases for GNSS-denied positioning). Ten papers contribute (mean TRL 3.9).

Environmental Sensing Layer captures the time-varying physical fields that directly affect flight safety. Three sub-domains are identified: electromagnetic environment modeling, target sensing and countermeasure (detection, classification, and tracking of non-cooperative objects), and micro-meteorological mapping (wind fields, turbulence, microclimate, fog). This is the most extensively studied layer with 19 papers (mean TRL 4.4) and 8 field-validated results.

Interaction Layer addresses the information exchange, trust establishment, and coordination mechanisms among heterogeneous system entities — UAVs, base stations, cloud platforms, and regulatory bodies. It covers network trust evaluation, data security and privacy, swarm performance assessment, and platform reliability monitoring. Six papers contribute (mean TRL 3.5).

The layers interact through three data flow pathways. Geospatial→Sensing: the 3D urban model defines the geometric domain for electromagnetic propagation modeling (Jiang et al., 2024) and microclimate simulation (Qin et al., 2025). Sensing→Interaction: cooperative detection results feed into trust evaluation modules that classify targets as authorized or malicious (Wang Y. et al., 2025a; Hu et al., 2025). Interaction→Geospatial: GNSS spoofing detection (Zhou J.W. et al., 2025) triggers fallback to vision-based positioning using semantic landmarks, recalibrating the positioning reference from the Geospatial Layer.

3. Geospatial Infrastructure Layer

This foundational layer provides the spatial skeleton and navigation reference for the Digital Twin. Ten papers contribute across four sub-domains (mean TRL 3.9, two field-validated).

3.1 Terrain Models and Ground Infrastructure

Zhang et al. (2018) (TRL 7) generated a 0.15 m resolution DEM via UAV photogrammetry (vertical RMSE 13.0 cm, horizontal RMSE 7.9 cm), validating the precision achievable with low-cost platforms. While oblique photogrammetry and LiDAR are mature surveying technologies (Biljecki et al., 2015), their

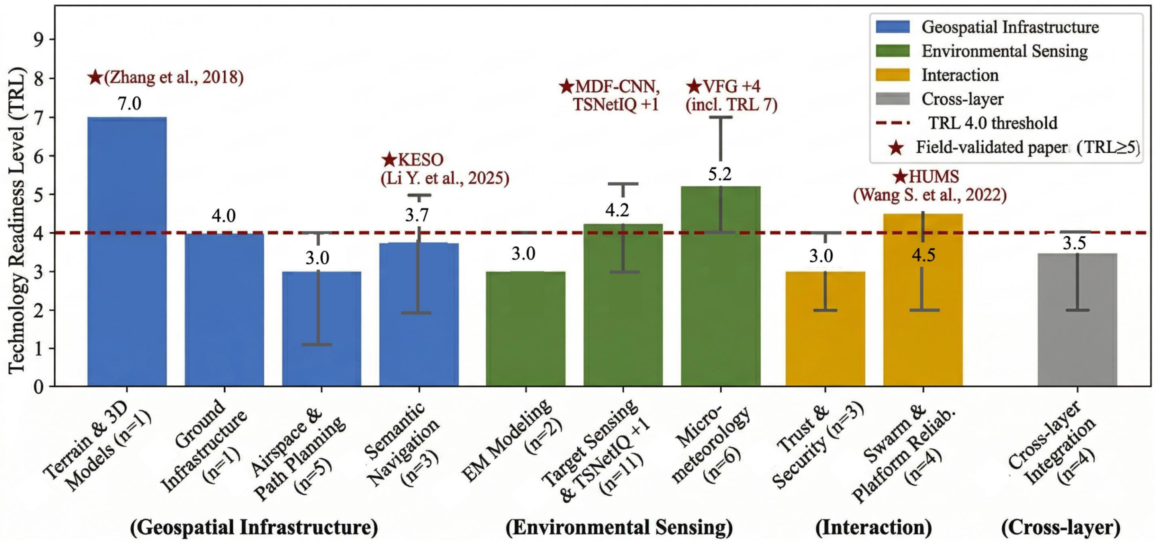

Figure 2. Technology Readiness Level comparison across framework layers. Grouped bar chart with mean TRL per sub-topic; papers achieving TRL ≥ 5 annotated; dashed line at TRL 4 marks the simulation-validation threshold.

formal integration into LAE Digital Twin frameworks — with specified Level-of-Detail requirements and update protocols — remains an open standardization task.

For ground infrastructure, Liu J. et al. (2025) present a three-stage framework for the Beijing—Tianjin—Hebei region: AHP-based multi-criteria suitability evaluation using 21 indicators and multi-source data (nighttime light imagery, DEM, POI, road networks), modified gravity model for hierarchical route construction (114 primary + 180 secondary + 366 tertiary routes), and spatial syntax evaluation with equity assessment (Gini coefficient reduced from 0.570 to 0.520; network maintains 98% connectivity under 10% random node removal). Furthermore, scaling these localized suitability models into comprehensive, globally distributed datasets—such as building a standardized global helipad dataset—remains a critical research gap for enabling ubiquitous and cross-regional LAE deployments.

3.2 Airspace Structure Digitalization

Five papers address the conversion of airspace regulations into machine-readable spatial representations. Lei et al. (2024) propose a five-layer vertical segmentation (0—120 m) with hybrid ACO-PSO path planning (22% fitness improvement). Yang et al. (2025) extend to 4D spatiotemporal trajectory planning. Liu F. et al. (2024) establish algorithmic foundations for spherical geodesic path planning (33% improvement over baseline GBO across 50—1,000 city scales). Li Z.M. et al. (2025) develop parametric models for UAV departure and arrival routes. Ben Dor and Hoffman (2022) contribute a legal framework proposing four-region airspace rights division, highlighting the unaddressed need for geo-referenced regulatory boundary encoding.

3.3 Semantic Navigation Landmarks

Li Y. et al. (2025) present KESO, which calibrates billboard corner keypoints via RTK-GPS, constructs a database indexed by semantic category and azimuth, and achieves UAV localization through YOLOv8n-seg detection (mAP50 = 99.5%), edge fitting, and UPnP pose solving. Field-validated on two Nanjing streets, KESO achieves RMSE of 2.54—4.08 m with 30—57% improvement over the POI-based baseline. The GNSS spoofing detection system (Zhou J.W. et al., 2025) complements this by providing a fallback mechanism (89.5% detection accuracy, 89.7% of recovered positions within 13.9 m). A BEV-based perception framework (Fan et al., 2024) offers a conceptual pathway for future scene understanding.

The semantic keypoint database is functionally analogous to vertiport siting or airspace boundary delineation — it is a spatial data product built before flight and maintained over time. The critical scalability challenge is that current databases require manual RTK calibration (61 targets); automated generation from existing 3D city models (Biljecki et al., 2015) is an important future direction.

The most significant gap across the Geospatial Infrastructure Layer is not in individual technologies but in their integration: no reviewed paper demonstrates a unified data infrastructure combining 3D models, infrastructure locations, airspace boundaries, and semantic landmark databases into a single queryable Digital Twin.

4. Environmental Sensing Layer

With 19 papers and the highest mean TRL (4.4), this is the most actively researched layer. Two dominant pillars emerge: target sensing and countermeasure (12 papers) and micro-meteorological mapping (6 papers), with electromagnetic modeling (3 papers) as a connecting thread.

4.1 Electromagnetic Environment and Target Sensing

Jiang et al. (2024) introduce the Integrated Air-Ground Network (IAGN) architecture with stochastic geometry-based performance analysis. Zhao et al. (2025) propose a GenAI framework achieving ~15% improvement in worst-case secrecy rate for robust beamforming. While these establish theoretical foundations, no operational real-time electromagnetic map has been demonstrated.

Table 2 summarizes the 12 papers on target sensing across three technical directions. ISAC-based cooperative sensing: Wang Y. et al. (2025a) introduce Virtual Sensing Cells achieving 3D tracking RMSE < 0.5 m; two further papers (Wang Y. et al., 2025b; Tang et al., 2025) extend to UAV-assisted ISAC and multi-station tensor decomposition. Non-cooperative target classification: four complementary modalities include radar micro-Doppler CNN achieving 94% accuracy at 0.57 ms (Zhou H.C. et al., 2025), ubiquitous radar 1D ResNet-SE (Song et al., 2024), acoustic DOA via Transformer-CNN (Zhu K.Q. et al., 2025), and distributed particle filtering with +7% tracking accuracy (Han et al., 2025). Electromagnetic threat identification: four papers address deceptive jamming discrimination with >0.95 probability (Gong et al., 2025), joint communication-jamming with 1—8 dB gain (Li Z. et al., 2025), RIS-assisted anti-eavesdropping (Li J. et al., 2025), and cross-domain RF fingerprinting (Xiao et al., 2024). The critical gap is the absence of end-to-end multi-modal fusion.

Table 2. Environmental sensing technologies for the low-altitude Digital Twin.

Technology	Modality	Spatial Output	Resolution	TRL
ISAC Cooperative Sensing	RF (cellular)	3D position + velocity	< 0.5 m	4
Micro-Doppler Radar CNN	RF (echo)	Target class + track	Class-level	5
Frequency-Agile Jamming ID	RF (multistatic)	True/false label	Binary	3
Acoustic DOA	Sound (mic array)	3D direction	Degree-level	5
Distributed Particle Filter	Multi-sensor	Multi-target tracks	Track-level	4
UAV Wind Measurement	Flight dynamics	3D wind speed/dir	0.39 m/s RMSE	5
Radar Wind Field Retrieval	Doppler radar	2D wind grid	3 m	5
Neural Operator Microclimate	CFD + DL	3D wind + temp	~1 m	4
Turbulence Dataset (RWP)	Radar + radiosonde	Turbulence params	120 m vert.	5
Radiation Fog Modeling	WRF + tower obs	Fog probability	5 km	5

4.2 Micro-Meteorological Mapping

Six papers address this sub-domain across scales from point measurement to regional modeling. Zhu S.H. et al. (2025) (TRL 5) infer 3D wind from UAV flight controller logs via Random Forest (RMSE 0.39 m/s), transforming every operational UAV into a mobile wind sensor — an insight with profound implications for crowdsourced meteorological mapping. Li X.L. et al. (2025) (TRL 5) achieve 3-meter resolution wind field retrieval using a Variable Frozen Grid algorithm (12—25% improvement over uniform methods). Qin et al. (2025) (TRL 4) model 3D urban microclimate via localized Fourier Neural Operator at ~1 m resolution, nearly 50× faster than CFD. Meng et al. (2025) (TRL 5) contribute a nationwide turbulence dataset (0.12—3.0 km altitude, 120 m vertical resolution). Liu H.L. et al. (2025) (TRL 5) improve radiation fog prediction by recalibrating WRF boundary layer parameters. Zhou Z. et al. (2024) (TRL 7) provide the operational endpoint — forced landing flight testing where meteorological information is consumed for emergency trajectory planning. The micro-meteorological sub-domain is the most mature (mean TRL 4.8), but no paper provides a continuously updated, city-wide, meter-scale 3D meteorological map integrating all sources.

5. Interaction Layer

This layer addresses information exchange, trust establishment, and coordination mechanisms among heterogeneous system entities. Six papers contribute (mean TRL 3.5), with the widest per-paper TRL range (2—8).

5.1 Network Trust and Data Security

Hu et al. (2025) propose GDM-DTM, a four-consistency Group Decision-Making trust framework evaluating node trustworthiness through subjective, objective, global, and self-proof perspectives using multi-dimensional attribute data. Validated with 120 UAVs in the ONE Simulator, GDM-DTM achieves 85.04% accuracy and 91.66% F-score at 30% malicious node ratio, operating independently of ground infrastructure. Song et al. (2025) provide the architectural vision with a three-dimensional trust framework incorporating federated unlearning. Lv et al. (2025) addresses location data privacy through encrypted spatial queries using optimized space-filling curves (20—30% accuracy improvement). The collective gap is that trust values remain per-node scores rather than geo-referenced spatial map layers consumable by UTM systems. To overcome this fragmented representation, applying paradigms such as Mobile Network Digital Twins (MNDT) could effectively synchronize the logical network topology with physical airspace dynamics, providing a unified architecture for evaluating real-time interaction trust.

5.2 Swarm Coordination and Platform Reliability

Zhong et al. (2025) propose a Bayesian Network framework bridging expert intuition with observational data for swarm performance assessment, addressing the challenge of reliable predictions when operational data is scarce.

Wang S.B. et al. (2022) (TRL 8) — the highest TRL in the corpus — review helicopter Health and Usage Monitoring Systems (HUMS), demonstrating operationally deployed condition-based maintenance. Chen et al. (2024) construct a safety assessment knowledge graph (SACAS) for airworthiness certification. Li T. et al. (2024) provide an eVTOL commercialization roadmap. The adaptation of heavyweight HUMS to lightweight UAV fleets remains a fundamental re-engineering challenge. Table 3 summarizes the representative methods and their reported performance across the Interaction Layer sub-domains.

Table 3. Interaction Layer methods comparison.

Sub-domain	Reference	Method	Performance	TRL
Network Trust	Hu et al., 2025	GDM-DTM (4-consistency)	Acc. 85%, F1 91.7%	3
Trust Architecture	Song et al., 2025	Federated unlearning	MI → 0	2
Data Security	Lv et al., 2025	OSFC-FSQ (Hilbert curve)	+20—30% acc	4

Sub-domain	Reference	Method	Performance	TRL
Swarm Coordination	Zhong et al., 2025	Bayesian Network	Robust posterior	4
Platform Reliability	Wang S.B. et al., 2022	HUMS (multi-sensor)	Deployed	8
Airworthiness	Chen et al., 2024	SACAS knowledge graph	Auto retrieval	4

6. Discussion

6.1 Cross-Layer Integration

Only four papers address cross-layer problems (mean TRL 3.5, zero field validations). These share a common pattern — feeding one layer's output as another's constraint (e.g., weather data constraining route planning (Feng and Cao, 2025), wind estimation enabling robust path-following control (Shao et al., 2025)) — but none demonstrates a full closed-loop system where all three layers operate simultaneously with continuous bidirectional exchange.

6.2 Technology Readiness Comparison

Table 4 and Figure 2 present the comprehensive TRL assessment — a central contribution of this review.

Table 4. Technology Readiness Level assessment summary.

Layer	Sub-topic	Papers	TRL Range	Mean	Field (≥5)
Geospatial	Terrain & 3D Models	1	7	7.0	1
	Ground Infrastructure	1	4	4.0	0
	Airspace & Path	5	1—4	3.0	0
	Semantic Navigation	3	2—5	3.7	1
	Layer Total	10	1—7	3.9	2
Sensing	EM Modeling	2	3	3.0	0
	Target Sensing	10	3—5	4.1	3
	Micro-meteorology	7	4—7	4.8	5
	Layer Total	19	3—7	4.4	8
Interaction	Trust & Security	3	2—4	3.0	0
	Swarm & Platform	3	2—8	4.5	1
	Layer Total	6	2—8	3.5	1
Cross-layer		4	2—4	3.5	0
Overall		39	1—8	4.1	11

Four patterns emerge. (1) Environmental Sensing leads in maturity (mean TRL 4.4), with micro-meteorology at TRL 4.8. (2) Geospatial Infrastructure shows extreme heterogeneity: terrain modeling (TRL 7) coexists with airspace regulation digitalization (TRL 1). Semantic navigation (TRL 5 for KESO) bridges these extremes. (3) Interaction Layer combines frontier concepts with deployed systems (TRL 2—8), but no integration pathway connects them. (4) Cross-layer integration is the weakest link (mean TRL 3.5, zero field validations); even as individual technologies mature, the overall Digital Twin cannot be realized without cross-layer fusion and standardized interfaces.

6.3 Positioning, Limitations, and Outlook

This review differs from ISAC surveys (Jiang et al., 2024) by foregrounding spatial mapping products rather than signal processing metrics, from smart city CIM (Biljecki et al., 2015) by incorporating low-altitude-specific elements, and from HD Maps (Liu R. et al., 2020) by operating in unstructured 3D airspace. The 74% concentration of papers in 2025 confirms this is a formative field. Limitations include single-database search (WOS), reviewer-assigned TRL scores, and geographic concentration of research in China.

7. Conclusion and Future Directions

This review analyzed 39 papers through a three-layer mapping framework for the LAE Digital Twin. Three principal findings emerge. First, the Environmental Sensing Layer is the most mature (mean TRL 4.4), with micro-meteorological mapping (TRL 4.8) and target classification (94% accuracy, TRL 5) approaching operational readiness. Second, the Geospatial Infrastructure and Interaction Layers contain individually mature technologies (photogrammetry TRL 7, HUMS TRL 8) but lack integrative frameworks and standardized data formats. Third, cross-layer integration (mean TRL 3.5) is the most critical bottleneck.

Four priority research directions are identified: (1) Standardization — developing unified spatial data formats extending CityGML (Biljecki et al., 2015) and OGC SensorThings API for low-altitude products; (2) AI-enabled predictive mapping — leveraging GenAI (Zhao et al., 2025) and neural operators (Qin et al., 2025) to continuously generate predictive environmental maps; (3) Crowdsourced updating — exploiting every operational UAV as a mobile sensor (Zhu S.H. et al., 2025) to create dense real-time observational networks; and (4) Closed-loop integration — developing full-stack Digital Twin prototypes where all three layers operate simultaneously, validated through field trials.

Acknowledgement
This work was supported by the National Natural Science Foundation of China (Grant No. 42371453).

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