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Integrated communication–sensing–navigation–control for low-altitude digital-intelligent networks: architecture, enabling technologies, and experimental validation*

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Abstract: The rapid advancement of the low-altitude economy (LAE) necessitates a fundamental shift from fragmented systems toward deeply integrated communication, sensing, navigation, and control capabilities. To this end, this paper proposes a low-altitude digital-intelligent network (LADIN) as an overarching architecture, with integrated sensing and communication (ISAC) serving as the core enabling technology that pervasively unifies its three layers. At the heterogeneous infrastructure layer, we detail an ISAC waveform design based on orthogonal frequency division multiplexing, enabling dual-purpose hardware to simultaneously achieve high-speed data transmission and high-precision environmental sensing. Within the intelligent data fusion layer, ISAC's role expands into a multimodal fusion paradigm, providing the crucial electromagnetic sensing modality. This layer constructs a unified spatiotemporal feature space by introducing pluggable back-projection adapters and spatiotemporal modeling. These adapters systematically integrate heterogeneous data from ISAC, optical cameras, and light detection and ranging (LiDAR) by inverting their respective observation models, thereby overcoming representational disparities and association ambiguities. At the service and management layer, this coherent representation directly drives algorithmic processes and control policies. ISAC resources are virtualized into dynamically allocable assets, enabling closed-loop control that responds to the real-time state of the feature space, such as reconfiguring base station operational modes based on live situational awareness. Validation through multi-frequency collaborative sensing and multimodal fusion use cases demonstrates significant performance gains in tracking robustness, detection of near-zero radar cross-section targets such as balloons, and seamless urban airspace governance, conclusively establishing the transformative potential of a deeply integrated, ISAC-centric approach for future LAE systems.

Key words: Low-altitude economy; Integrated sensing and communication; Airspace management; Uncrewed aerial vehicles; Cyber-physical system
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1 Introduction

The low-altitude economy (LAE) represents a strategic frontier in airspace resource utilization, rapidly evolving toward intelligent and coordinated operations (Wang YX et al., 2025). Central to this development are LAE networks (LAENets), which integrate uncrewed aerial vehicles (UAVs) with terrestrial digital systems to support critical

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ORCID: Qixun ZHANG, https://orcid.org/0000-0003-0055-3062 applications such as urban logistics (Wei et al., 2024), infrastructure inspection, and emergency services (Zaid et al., 2023). Beyond mere communication links, LAENets constitute the foundational digital infrastructure for dynamic airspace management and safety governance, with their maturity directly determining the LAE's commercial scalability.

These applications demand persistent situational awareness, high-precision positioning, reliable communication, and scalable management from LAENets (3GPP, 2024). Yet current architectures exhibit fundamental fragmentation, resulting in detection failures, connectivity gaps, and control deficiencies. Urban environments particularly highlight these issues, with low UAV detection rates, unreliable network links, and inflexible airspace management creating operational bottlenecks and safety concerns (Gao et al., 2024). More critically, poor subsystem coordination risks cascading failures, such as communication disruptions triggering navigation breakdowns (Chen et al., 2024), underscoring the urgent need for deeply integrated systems (Jiang et al., 2024; He et al., 2025).

In response to the operational challenges in LAE, significant research efforts have focused on cross-domain integration of communication, sensing, navigation, and computing capabilities. For communication and sensing integration (Zhang et al., 2022, 2024; Sun et al., 2024; Zhu et al., 2024), advances include adaptive waveform designs that dynamically balance sensing–communication performance (Huang YQ et al., 2025), networked integrated sensing and communication (ISAC) frameworks enabling multi-station coordination for continuous UAV tracking and handover (Cheng et al., 2025; Zhao CB et al., 2025), and comprehensive studies of LAE-specific ISAC opportunities and challenges (Jiang et al., 2025), with some extending to integrated communication, jamming systems for counter-UAV operations (Li ZR et al., 2025). In communication and navigation integration, research has yielded carrier-phase enhancements in the 5th generation mobile communication technology (5G)-advanced (5G-A) networks for high-precision positioning (Nikonowicz et al., 2024), cooperative navigation strategies for UAV swarms (Wang R et al., 2025), and artificial intelligence (AI)-enhanced schemes for joint navigation–communication control (Eskandari and Savkin, 2023) and massive multiple-input multiple-output (MIMO)-optimized navigation (Huang HJ et al., 2020). Critically, the dimension of control remains narrowly defined in existing works, primarily focusing on resource management. This is evident in the domain of communication and computing integration, which has produced solutions for joint resource allocation in integrated sensing–communication–computing scenarios (Liu et al., 2024), intelligent task offloading mechanisms in multi-UAV edge computing systems (Xia et al., 2022), and multi-agent learning frameworks for distributed computation (Zhao N et al., 2022). However, a broad and equally critical aspect of control—the direct management of UAV missions and behaviors, such as trajectory planning and airspace governance—has not been cohesively integrated into this framework.

Nevertheless, these achievements remain confined to localized optimizations of dual-function combinations, resulting in incompatible performance objectives and protocol mismatches during system integration. This fragmented approach reveals a critical gap: the absence of a holistic architecture that unifies sensing, connectivity, localization, control, and computing. Such comprehensive integration is indispensable for establishing seamless sensing–decision–control loops in large-scale LAE operations. To bridge the aforementioned research gap, this paper makes the following key contributions:

1. We propose a low-altitude digital intelligent network (LADIN), a novel architectural framework that, for the first time, establishes an end-to-end integrated communication, sensing, navigation, and control (CSNC) system. By transcending the limitations of conventional fragmented systems, LADIN provides a unified foundation that enables robust, closed-loop cyber-physical intelligence for low-altitude operations.

2. We investigate and implement a suite of core enabling technologies, with ISAC serving as a pervasive thread throughout the LADIN layers. This includes an orthogonal frequency division multiplexing (OFDM)-based ISAC waveform design at the infrastructure layer for dual-purpose hardware, the construction of a unified back-projection spatiotemporal feature space (USFS) via pluggable adapters and spatiotemporal modeling at the data fusion layer, and the virtualization of ISAC resources for intent-driven, closed-loop control at the service and

management layer.

3. We develop a multimodal hardware testbed that physically embodies the LADIN architecture. Through comprehensive field experiments, including ISAC functionality validation, multi-frequency collaborative sensing, multimodal fusion for challenging near-zero radar cross-section (RCS) targets, and a management platform demonstration—we provide extensive experimental validation, demonstrating significant performance gains in tracking robustness, target identification accuracy, and operational governance efficacy.

2 LADIN architecture

As the LAE transitions toward large-scale deployment, its supporting infrastructure necessitates a fundamental shift from fragmented systems to deeply integrated intelligence. Conventional architectures, characterized by segregated CSNC systems, create operational silos with inherent limitations. These isolated systems introduce significant inter-system latency, suffer from mutual interference among sensing, navigation, and communication signals, and incur high costs for deploying dedicated sensing infrastructure, resulting in poor coverage and inefficient resource allocation. These deficiencies collectively compromise the safety and scalability of airspace management. To address these critical challenges, we propose the LADIN architecture, as shown in Fig. 1, a three-layer framework comprising the heterogeneous infrastructure layer, intelligent data fusion layer, and service and management layer. This integrated CSNC design establishes an end-to-end cyber–physical loop that unifies multimodal hardware abstraction, enables dynamic data fusion for constructing a coherent physical–digital representation, and delivers closed-loop decision support for diverse aerial applications.

The performance of the LADIN architecture depends on advanced sensing capabilities enabled by multimodal ISAC. In complex LAE scenarios, ISAC is not merely an optional feature but a fundamental component. It evolves from fixed hardware into

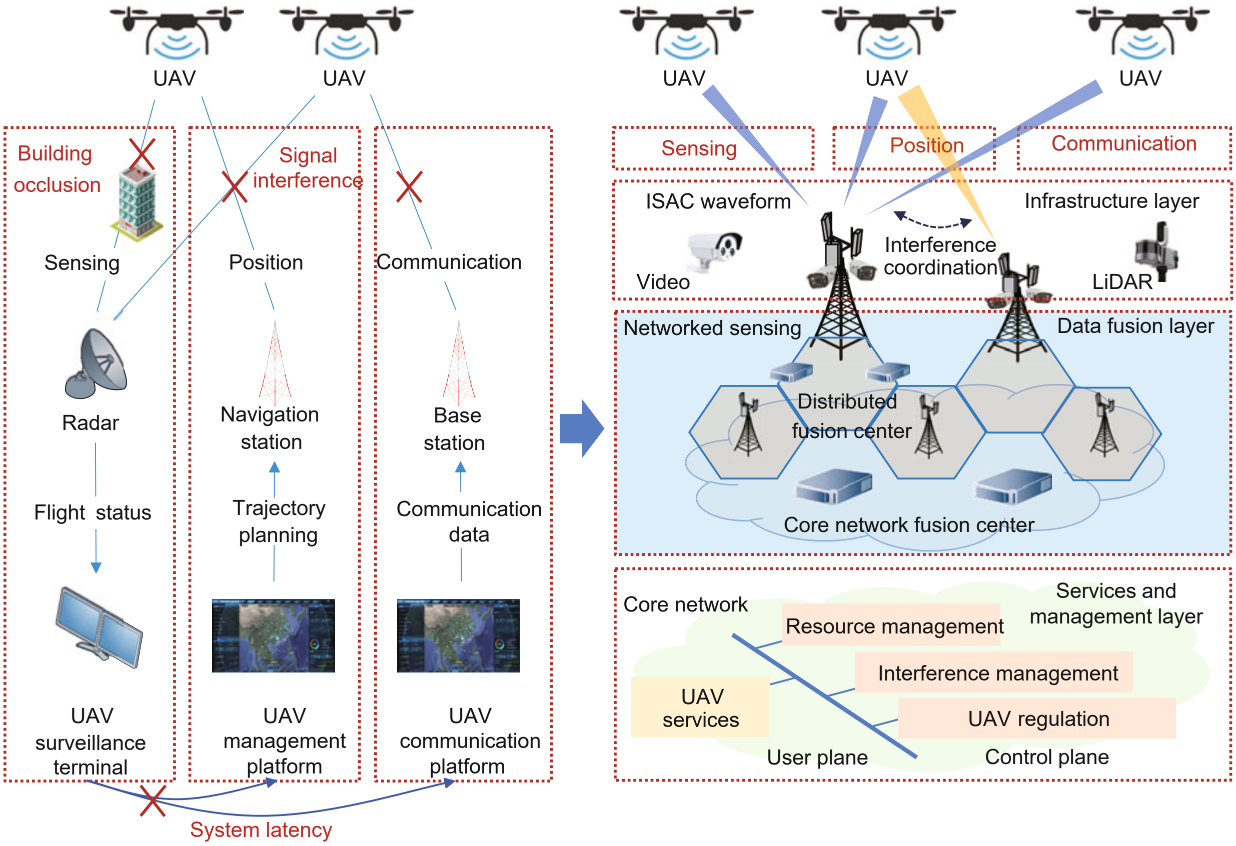


Fig. 1 Comparison of conventional disjoint architecture and the proposed LADIN

reconfigurable functions that are integrated across all three layers. This integrated approach systematically counters the inherent limitations of traditional fragmented systems: (1) It mitigates building occlusion through networked sensing, where ISAC-enabled base stations (BSs) function as collaborative sensing nodes to provide ubiquitous coverage and seamless target tracking across coverage boundaries. (2) It reduces mutual interference at its source via unified ISAC waveform design, which inherently coordinates communication and sensing signals and avoids conflicts typical of co-located but independent systems. (3) It diminishes system latency through deeply integrated core-network-based management, where functions such as interference coordination and resource control are implemented as internal network elements, avoiding the delays associated with inter-system communication.

Beyond addressing these limitations, the architecture's design is inherently resilient to the critical challenge of information absence, an issue arising from practical operational conditions, such as temporary sensor occlusion, hardware failure, or low-observability targets. This capability is rooted in the deep integration across the three layers. At the infrastructure layer, ISAC enables dual-purpose hardware—repurposing communication BSs into sensing nodes—to simultaneously achieve high-speed data transmission and high-precision environmental sensing. Within the intelligent data fusion layer, the systematic integration of heterogeneous sensor data via pluggable back-projection adapters and spatiotemporal modeling yields the USFS, which is essential for predicting target states and maintaining coherent awareness during periods of missing data. Leveraging the USFS, the service and management layer virtualizes ISAC resources into dynamically allocable assets that translate operational intent into optimized physical-layer configurations, enabling proactive resource reconfiguration, such as steering sensing beams toward anticipated blind spots, to actively compensate for information absence. Together, these mechanisms ensure the continuity and reliability of the cyber-physical loop across varying mission demands and environmental conditions.

1. Infrastructure layer

At this layer, the core breakthrough of ISAC lies in the deep synergy between hardware and waveform design. Through innovative ISAC waveform design and reconfigurable radio frequency (RF) front-ends, a single hardware unit can simultaneously achieve high-speed data transmission and high-precision environmental sensing. Specifically, the system employs an OFDM-based waveform structure where phase variations across subcarriers and symbols are analyzed to extract target range and velocity information. This approach enables the same hardware to perform communication and sensing functions without mutual interference. It not only significantly improves the utilization efficiency of low-altitude spectrum and hardware resources but also lays the physical groundwork for building a streamlined, cost-effective low-altitude coverage network. Positioned at the network edge, the ISAC nodes collect raw communication status and environmental echoes, process them into standardized multimodal sensing data streams, and continuously supply this information to support upper-layer cognitive decision-making.

2. Intelligent data fusion layer

The multimodal data streams converging at the intelligent data fusion layer undergo deep processing and refinement through a unified three-dimensional (3D) feature space architecture. This innovative framework addresses the fundamental challenges of multimodal fusion by establishing a common digital coordinate system where all sensor observations are represented consistently. The system employs pluggable back-projection adapters to accommodate different sensor types. These adapters effectively transform heterogeneous data from ISAC, optical cameras, and light detection and ranging (LiDAR) into unified semantic representations by inverting their respective observation models.

Furthermore, the system models this integrated data along the temporal dimension to construct the USFS, which inherently enables the system to maintain situational awareness even during periods of information absence by predicting and extrapolating target states based on learned spatiotemporal dynamics. At this stage, the connotation of ISAC extends from hardware design to the flexible scheduling of algorithms and computational resources. These algorithm modules, existing in a software-defined, modular form, can be flexibly loaded and executed across different computational entities, from distributed edge nodes to central cloud resources. For instance, in wide-area UAV swarm tracking missions, the fusion center can dynamically coordinate sensing data from multiple BSs to generate unified tracks through collaborative signal processing. For fine-grained identification in specific regions, it can trigger feature-level fusion processes between visual and radar data. This architecture effectively overcomes representational disparities and association ambiguities, ensuring that the system can distill continuous and reliable domain-wide situational awareness from multi-source, redundant, and even partially conflicting data.

3. Service and management layer

The refined and precise situational information from the fusion layer, encapsulated within USFS, is directly used by the service and management layer to drive intelligent decision-making. This layer establishes a closed-loop control system that enables not only real-time monitoring but also proactive intervention in the low-altitude environment. The architecture implements a control and user plane separation (CUPS) principle, creating an independent low-altitude UAV management network that ensures deterministic performance for critical control functions. At this top level, the value of ISAC evolves into an advanced "Resource-as-a-Service" paradigm, manifested as virtualized resource units that can be dynamically invoked by the management layer. When the analysis of the USFS indicates a suspected unauthorized UAV in the specific airspace, the service management layer not only generates alerts but also dynamically reconfigures the operational mode of the regional ISAC BSs through southbound interfaces, such as by temporarily increasing the scanning frequency of sensing beams, optimizing the power allocation strategy between communication and sensing, or commanding optical sensors to initiate collaborative verification. This intent-driven control similarly applies to anticipated information absence: upon detecting growing uncertainty or a predicted trajectory entering a blind spot, the system proactively reconfigures ISAC beams to enhance coverage, thereby compensating for potential data loss before it impacts safety. This real-time, on-demand allocation of ISAC resources achieves a fundamental shift from static configuration to dynamic empowerment, enabling network resources to proactively adapt to and guarantee the requirements of upper-layer applications, thereby demonstrating unprecedented agility and precision in core functions such as resource management, interference control, and UAV supervision.

3 Envisioned application scenarios and system potentials

The proposed LADIN architecture and its core ISAC technologies are designed to pave the way for advanced low-altitude operations. The following scenarios illustrate the targeted capabilities and long-term potential of the system, which our current research aims to enable through continued development.

1. Ubiquitous wide-area surveillance

The LADIN architecture is designed to transcend the limitations of single-station detection. Future implementations could leverage the networked ISAC framework to achieve seamless target tracking across coverage boundaries. The multimodal fusion algorithms explored in this work provide a foundational pathway toward this goal, with the potential to enable cost-effective, large-scale airspace monitoring that is currently infeasible with isolated systems.

2. Electromagnetic resilience

Operating in contested spectrum environments remains a significant challenge. The LADIN architecture proposes a cohesive approach that integrates real-time spectrum sensing with communication functions. This approach lays the groundwork for future systems capable of dynamically characterizing the electromagnetic environment, identifying interference sources, and autonomously reconfiguring operational parameters to maintain both communication and sensing performance under adverse conditions.

3. Dynamic and predictive coverage

During LAE demonstration zone development, the deployment locations of 5G-A integrated BSs critically determine the coverage performance. Post-deployment coverage deficiencies lead to costly reconstruction. Coverage simulation and assessment enable predictive analysis during planning by modeling ground/air environments against airspace zoning and operational requirements. This methodology provides data-driven network planning support, effectively preventing coverage blind spots.

4. Autonomous and secure airspace management

Real-time fully autonomous airspace control requires a reliable distinction between authorized and unauthorized aircraft. The multimodal data fusion capabilities central to LADIN represent a critical step toward this capability. Future work building on this foundation could achieve the robust situational awareness needed for automated anomaly detection, risk assessment, and coordinated response, thereby supporting the safe and efficient integration of dense UAV traffic.

4 Enabling multimodal ISAC

4.1 Infrastructure layer: OFDM-based ISAC waveform design

To materialize the ISAC capability at the infrastructure layer, we present an ISAC signal model based on the OFDM waveform as shown in Fig. 2, which serves as the physical basis for the LADIN architecture.

Let n and m denote the indices of the OFDM symbol (for sensing) and subcarrier, respectively. The transmitted signal is represented by the resource grid $G_{\mathrm{x}}(n,m)$. Assuming Q targets with kinematics modeled as $R_q(t)=v_q t+R_0$ $(q=1,2,...,Q)$ within the coherence time, the received baseband signal—after OFDM modulation, RF modulation, and target reflection—is obtained by

$$G_{\mathrm{y}}(t)=\sum_{q=1}^{Q}A_q s\left(\frac{t-2R_q(t)}{c}\right)\mathrm{e}^{-\mathrm{j}2\pi f_{\mathrm{ca}}\frac{2(v_q t+R_0)}{c}}, \tag{1}$$

where v_q is the speed of the q^{th} target, R_0 is the initial distance from the BS to the target, $s(\cdot)$ is the transmitted signal, A_q is the channel attenuation factor, f_{ca} is the carrier frequency, and c is the speed of light. After OFDM demodulation, the signal on the resource grid at the receiver becomes

$$\begin{aligned}G_{\mathrm{y}}(n,m)=&G_{\mathrm{x}}(n,m)\sum_{q=1}^{Q}A_q\mathrm{e}^{-\mathrm{j}2\pi m\Delta f\frac{2(v_q nT_{\mathrm{s}}+R_0)}{c}}\\&\cdot\mathrm{e}^{-\mathrm{j}2\pi f_{\mathrm{ca}}\frac{2(v_q nT_{\mathrm{s}}+R_0)}{c}},\end{aligned} \tag{2}$$

where Δf is the subcarrier spacing and T_{s} is the sensing symbol period. To isolate the target motion information, we divide the received signal by the transmitted signal on the resource grid, obtaining a cleaned channel state information (CSI) model:

$$\begin{aligned}G_{\mathrm{div}}(n,m)&=\frac{G_{\mathrm{y}}(n,m)}{G_{\mathrm{x}}(n,m)}\\&\approx\sum_{q=1}^{Q}A_q\mathrm{e}^{\frac{-\mathrm{j}2\pi(m\Delta f\cdot 2R_q+f_{\mathrm{ca}}\cdot 2v_q nT_{\mathrm{s}}+f_{\mathrm{ca}}\cdot 2R_0)}{c}}.\end{aligned} \tag{3}$$

The phase terms in $G_{\mathrm{div}}(n,m)$ reveal how target information is encoded: the term $\mathrm{e}^{-\mathrm{j}2\pi\frac{m\Delta f\cdot 2R_q}{c}}$ enables range estimation via fast Fourier transform (FFT) along the subcarrier dimension. The term $\mathrm{e}^{-\mathrm{j}2\pi\frac{f_{\mathrm{ca}}\cdot 2v_q nT_{\mathrm{s}}}{c}}$ enables velocity estimation via FFT along the symbol dimension. The constant term $\mathrm{e}^{-\mathrm{j}2\pi\frac{f_{\mathrm{ca}}\cdot 2R_0}{c}}$ has no effect on the estimation.

Based on this model, we have developed a CSI-based ISAC method for target detection. The decoupling model accurately extracts target range and velocity by analyzing phase variations across subcarriers and symbols, respectively. The framework demonstrates high flexibility, enabling it to reuse standard comb-type pilots for basic sensing (Zhang et al., 2024) or to employ dedicated sequences for enhanced performance (Zhang et al., 2022). Furthermore, by incorporating advanced signal processing techniques such as inverse synthetic aperture radar (ISAR) imaging and micro-Doppler feature extraction, the proposed method can resolve high-resolution range profiles and micro-motion

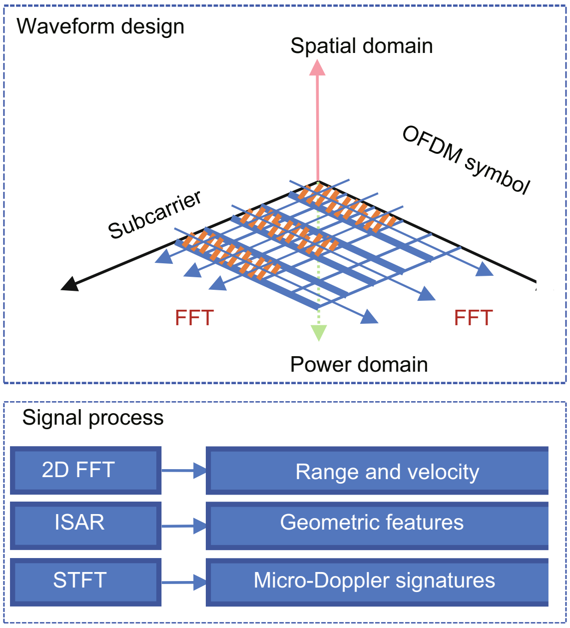


Fig. 2 ISAC signal design in multiple domains and associated processing techniques. STFT: short-time Fourier transform

characteristics of targets. These deep features provide critical support for accurate target identification and fine-grained classification, and can serve as input for the electromagnetic sensing modality, laying the foundation for constructing a unified multimodal feature space.

In 5G new radio (NR), the collaboration between communication and sensing extends beyond time–frequency resources to include the power and spatial domains. According to 3GPP standards, the system can flexibly configure the transmit power of reference signals and data payloads by adjusting power offsets. In sensing scenarios, when time–frequency resources are limited, sensing performance can be maintained by increasing the power of reference signals. Meanwhile, by leveraging massive antenna beamforming and flexible resource mapping, communication and sensing signals can be multiplexed in the spatial domain to serve multiple users with diverse requirements in different directions. Ultimately, through coordinated design and scheduling of communication and sensing signals, efficient utilization of multi-dimensional resources can be achieved.

4.2 Data fusion layer: extensible multimodal fusion architecture

The data fusion layer in the LADIN architecture constructs a USFS by systematically integrating sensor data across spatial and temporal dimensions, as shown in Fig. 3. This process directly addresses the limitations of conventional fusion methods, which struggle with data-level heterogeneity and association ambiguity. Instead, our approach reframes the challenge as a structured problem of model inversion.

Fusion is achieved through pluggable back-projection adapters, which are designed by first modeling the forward sensing process, from the physical world to each modality's observation space. Sensors are thus viewed as performing distinct dimensional projections (e.g., millimeter-wave (mmWave) radar in the range, Doppler domain and visual sensors as perspective projections). The adapters then invert these known transformations to project all heterogeneous, low-dimensional observations back into a common multimodal unified sensing space. This space—a discretized 3D grid—resolves heterogeneity and ambiguity by providing a unified coordinate system, effectively reconstructing high-dimensional features from low-dimensional observations.

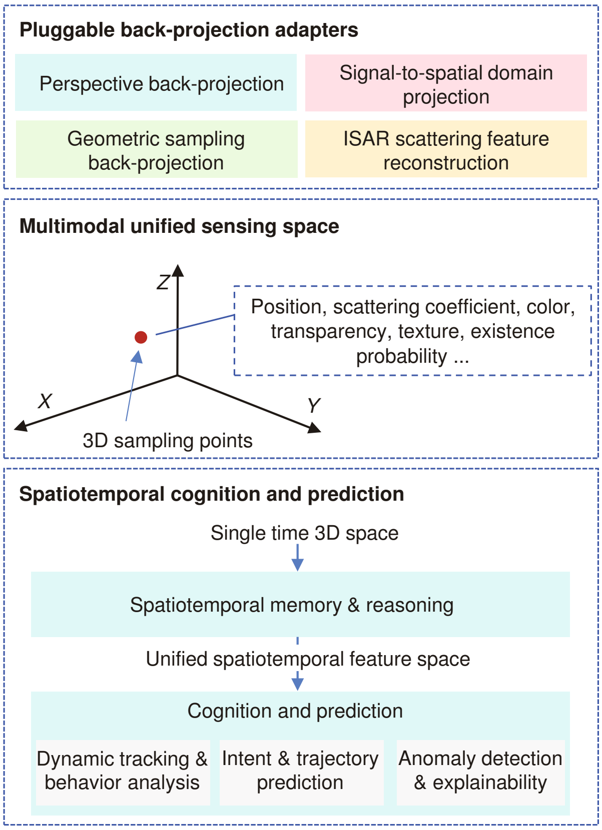


Fig. 3 Hierarchical data processing pipeline of the data fusion layer

The USFS is subsequently built upon this foundation through spatiotemporal modeling. By accumulating and analyzing a sequence of frames from the multimodal unified sensing space, the system forms a dynamic four-dimensional (4D) representation that captures both spatial structure and its temporal evolution, thereby enabling coherent and continuous situational awareness.

4.2.1 Pluggable back-projection adapters

Each sensor modality (e.g., vision, mmWave radar, LiDAR, and ISAR) incorporates a dedicated back-projection adapter that encapsulates its specific observation geometry and physical characteristics. For optical cameras, the adapter employs intrinsic and extrinsic parameters to back-project image-based features (such as bounding boxes and texture information) into corresponding line-of-sight (LOS) frustums within the feature space. Radar adapters use signal models to map point detections or ISAR scattering features into appropriate range–azimuth cells. This adapter layer effectively transforms heterogeneous sensor data into unified semantic representations, thereby establishing the foundation for system extensibility.

4.2.2 Multimodal unified sensing space

Following back-projection, multimodal features aggregate within the unified sensing space. Individual voxels may concurrently contain electromagnetic scattering characteristics from radar, visual texture features, and geometric information from LiDAR. This unified representation simplifies subsequent processing: target association reduces to identifying feature clusters in the spatial domain, while multi-station fusion naturally occurs through coordinate system unification. A deep spatial reasoning network (e.g., a 3D convolutional neural network or PointNet++) operating directly on this feature space enables end-to-end learning for detection, classification, and tracking tasks, effectively addressing occlusion and conflict resolution.

4.2.3 Spatiotemporal cognition and prediction layer

The unified sensing space forms a coherent 4D representation from a sequence of frames, which we define as the USFS. A spatiotemporal memory and reasoning module, powered by networks like 3D convolutional long short-term memory (LSTM) or Transformers, performs spatiotemporal modeling on this USFS to learn scene dynamics. This process enables three key capabilities: (1) dynamic tracking and behavior analysis—moves beyond spatial association to track targets based on the predicted trajectories and behavioral consistency, identifying maneuvers like overtaking or sudden deceleration; (2) intent and trajectory prediction—forecasts probabilistic future paths for agents by modeling their interactions with the environment and other dynamic targets; (3) anomaly detection and explainability—flags deviations from learned normal patterns and provides causal explanations for predictions via attention mechanisms.

The proposed USFS delivers three key system-level advantages. First, it introduces a consistent fusion paradigm that reformulates multimodal fusion as a structured spatial integration task, significantly streamlining algorithm design. Second, the system is highly extensible—adding new sensor types only requires developing corresponding pluggable back-projection adapters, without modification to the core fusion logic. Third, the framework inherently enhances robustness and accuracy by fusing complementary multi-view and multimodal information, ensuring reliable performance even under partial sensor failure or challenging observation conditions.

4.3 Service and management layer: closed-loop intelligent control

The service and management layer serves as the decision-making and control core of the LADIN. As shown in Fig. 4, this layer builds directly upon the USFS provided by the intelligent data fusion layer. By incorporating real-time dynamic data, business rules, and physical constraints, it transforms the coherent situational awareness of the USFS into actionable control policies, enabling not only precise mapping and prediction but also active intervention in the actual low-altitude environment.

The architectural design adopts the CUPS principle, establishing a low-altitude UAV management network independent of the public Internet. This achieves decoupling of the control plane from the mission data flow at logical and physical levels, ensuring determinism for high-reliability services, including flight commands, conflict resolution, and emergency interventions. By isolating control traffic,

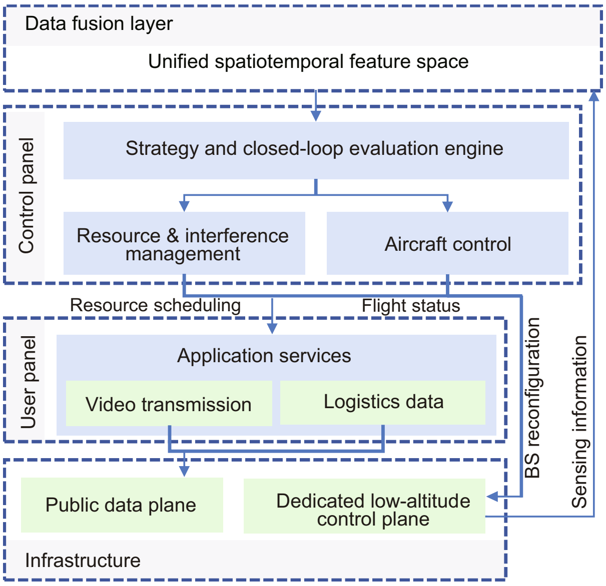


Fig. 4 Closed-loop control architecture for UAV and ISAC resource management

the system prevents failures caused by public network congestion or service competition, making it suitable for the safety management of large-scale UAV clusters.

In the area of communication–sensing resources and electromagnetic management, the system abstracts communication, sensing, and positioning resources as virtual assets that can be dynamically scheduled based on the operational demands derived from the USFS. Using the ISAC technology, the system dynamically adjusts BS waveforms and sensing symbol configurations based on traffic predictions and identified sensing blind spots. This resource reconfiguration capability is pivotal in proactively compensating for anticipated information absence, such as by steering sensing beams to cover regions where data loss is predicted. It leverages MIMO and beamforming for multi-station collaboration to enhance coverage. For spectrum management, the system combines heterogeneous networks, composed of 5G-A/automated-to-everything (A2X) and RedCap, with network slicing technology to allocate dedicated slices for the control plane, ensuring command link priority. Upon detecting interference, the system performs multi-station collaborative localization and dynamic frequency switching to achieve effective spectrum governance.

In the domain of aircraft management and control, the system relies on the independent control network to achieve full lifecycle management of UAVs. Through core network functions such as UAV access gateway function (UAGF), UAV access control function (UACF), UAV radio resource management function (UARF), and UAV application management function (UAMF), a unified access and control channel is established. This enables the regulatory system to issue mandatory commands, such as hover, land, or return-to-base, to cooperative UAVs without relying on manufacturers, thereby ensuring rapid response to anomalous behaviors. For high-density flight scenarios, the system introduces a hierarchical situation evolution framework: at the local level, evolutionary game theory is used to achieve route equilibrium, while at the global level, Monte Carlo tree search is employed for the multi-agent trajectory optimization, enhancing cluster operational efficiency and stability.

The core decision engine continuously interprets the USFS to anticipate service demands and operational risks. This analysis enables the engine to parse high-level strategies into specific, executable control parameters. These parameters are first validated against the USFS to simulate their outcomes and ensure feasibility before being distributed for execution. Dynamic adjustments are made based on real-time feedback from sensing and positioning data, forming a complete sensing–decision–control closed loop. To support wide-area operations, the system adopts hierarchically deployed UARF and UACF, enabling seamless handover of control links for UAVs in cross-domain and cross-province scenarios. Through UAGF re-anchoring and signaling coordination between UARFs, the system maintains persistent air–ground link connectivity and state synchronization, achieving seamless supervision.

5 Hardware testbed

To evaluate the LADIN architecture's sensing performance and collaborative efficacy in complex low-altitude environments, we develop a multimodal hardware test platform, as shown in Fig. 5. This platform physically embodies the three-layer LADIN structure, integrating a 5G NR mmWave ISAC subsystem and an optical vision subsystem via a unified local area network (LAN). The fusion host acts as the system core, handling data aggregation, intelligent processing, and situational presentation, directly mirroring the LADIN workflow from the heterogeneous infrastructure layer, through the data fusion layer, to the service and management layer. This platform enables validation of deep ISAC–visual integration at both data and decision levels and assessment of system-level advantages in overcoming typical low-altitude challenges like occlusion, classification ambiguity, and blind spots.

The ISAC module forms the sensing foundation of the platform, embodying the core ISAC principle of hardware–waveform synergy. Built on a shared 5G NR mmWave platform, it reuses RF and baseband resources for both communication and sensing. Operating at 26 GHz with a total bandwidth of 800 MHz, it dynamically allocates 100 MHz for sensing, balancing communication rate and sensing accuracy. The RF link uses 256-element phased array antennas for high-gain directional beams and spatial scanning. The BS configures frequencies and beams via a serial interface, handling integrated waveform

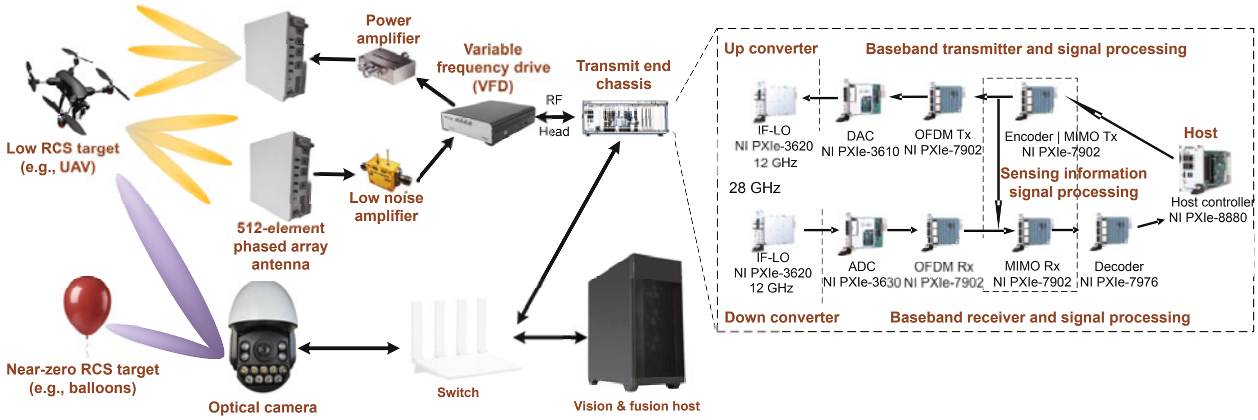


Fig. 5 Multimodal ISAC hardware testbed. DAC: digital-to-analog converter; ADC: analog-to-digital converter

transmission and echo reception. All signal processing is performed at the BS, outputting high-level sensing data like target range, velocity, and azimuth. This integrated, software-defined design enables dynamic “Resource-as-a-Service” scheduling in the upper architecture layers.

The visual modality complements ISAC sensing by providing high-resolution texture and semantic classification. The optical camera streams RGB video to the fusion host, while the vision branch uses YOLOv5x for object detection, outputting bounding boxes and class labels under clear conditions. To address optical challenges in complex scenarios, the platform employs the aforementioned data fusion mechanism. A spatiotemporal alignment module first synchronizes and maps ISAC-derived target coordinates and visual bounding boxes into a unified frame. A fusion network then associates targets and merges confidence scores, producing unified tracks with geographic location, motion parameters, and semantic labels. Crucially, a radar-assisted prior mechanism leverages ISAC-predicted positions as search regions for the visual detector when YOLO fails, thereby boosting re-acquisition probability. This intelligent feedback enhances robustness under partial observability, demonstrating LADIN’s cross-layer collaborative intelligence.

6 Application cases

6.1 Case 1: ISAC functionality validation

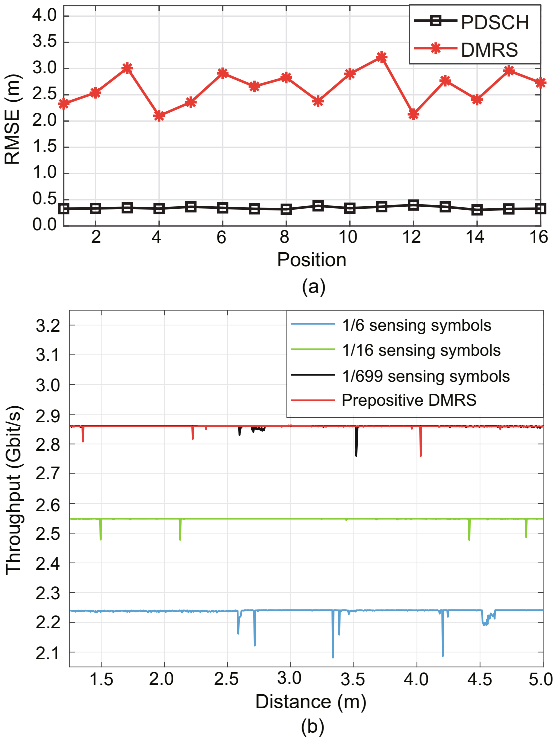
Based on the ISAC design in the aforementioned LADIN architecture, we conduct specialized validation of the ISAC link within the hardware test platform in a laboratory environment (Zhang et al., 2024). The test platform employs two 64-element phased array antennas with the equivalent isotropically radiated power (EIRP) of 51 dBm. The system operates at a center frequency of 26 GHz with a total bandwidth of 800 MHz (comprising eight component carriers), of which 100 MHz is dedicated to sensing. The frame structure has a duration of 10 ms, containing 50 slots, with each slot comprising 14 OFDM symbols modulated using 64-quadrature amplitude modulation (QAM).

The experiment uses a Baidu Apollo autonomous vehicle as the moving sensing target, while an independent communication receiver is added to simultaneously evaluate communication performance. The validation strictly follows the signal design scheme of the infrastructure layer, focusing on comparing two modes of ISAC resource utilization: one directly uses demodulation reference signals (DMRSs), and the other artificially embeds comb-shaped pilots in the physical downlink shared channel (PDSCH), systematically assessing the impact of different pilot densities on sensing performance.

The sensing performance test results in Fig. 6a show that the sensing accuracy based on the PDSCH scheme is significantly better than that of the DMRS scheme, with the root mean squared errors (RMSEs) of the distance estimation of 0.345 m and 2.640 m, respectively. This performance gap primarily stems from the higher resource density of PDSCH symbols in the time–frequency domain, which provides rich signal features for the sensing function. Although high-density sensing symbols can enhance sensing performance, the time-division ISAC architecture entails a fundamental trade-off between communication and sensing: as the density of sensing symbols increases, communication performance degrades, as illustrated in Fig. 6b. Nevertheless, the fully DMRS-based ISAC scheme achieves a data rate of 2.86 Gbit/s, demonstrating stable communication performance and confirming the transparency of pilot-based ISAC design for upper-layer communication services.

6.2 Case 2: multi-frequency collaborative ISAC

The field test for low-altitude UAV detection employs a dual-station ISAC setup, as illustrated in Fig. 7, to validate multi-frequency collaborative sensing. The system consists of a sub-6 GHz BS and a mmWave BS. The sub-6 GHz BS operates at 3.75 GHz with 100 MHz bandwidth and 46 dBm EIRP, using an omnidirectional antenna for transmission and a four-element array for reception, which employs phase-difference-based angle estimation. It is deployed for wide-area coverage. The mmWave BS operates at 26 GHz with 800 MHz bandwidth and 55 dBm EIRP, equipped with a 256-element phased array that performs beam scanning and amplitude-comparison angle measurement, with a main lobe width of 6°, enabling high-resolution, close-range detection. Both BSs use OFDM waveforms with embedded subcarrier radar sampling and operate in a monostatic sensing mode, measuring target azimuth in the horizontal plane with a refresh rate of 1 Hz. Each station outputs perceptual data, including range, angle, and velocity of multiple targets, to a centralized processor, where the sensing outputs are fused to generate a unified UAV trajectory.



(a)

(b)

Fig. 6 ISAC sensing and communication performance evaluation for different schemes: RMSE of the distance estimation for PDSCH and DMRS schemes (a) and throughput comparison between the proposed ISAC scheme with DMRS occupation and the time-division ISAC scheme in Zhang et al. (2022) (b)

As shown in Fig. 7a, these two BSs are deployed with perpendicular sensing orientations, and a building located between them partially obstructs the sensing sightlines. The experiment involves a DJI M300 UAV (RCS$\leq$0.1 m^2) taking off in front of the sub-6 GHz BS and flying along the path indicated by the red arrow in the figure. The UAV is not programmed to maintain a constant speed; instead, its velocity varied within the 1–5 m/s range throughout the flight. Initially detected only by the sub-6 GHz BS while moving north, the UAV enters the overlapping coverage zone where both BSs contribute to collaborative sensing. As it turns east, urban obstacles degrade the sub-6 GHz link, causing the mmWave BS to become the primary detector. This dynamic handover ensures continuous tracking.

To evaluate the positioning performance of multi-frequency ISAC fusion in complex urban environments, we conduct multiple independent experiments for three configurations: the sub-6 GHz BS, the mmWave BS, and the fused result. System accuracy is validated against the Global Positioning System (GPS) ground truth, with positioning errors under 10 m considered valid according to 3GPP TR 22.837. All 80 sampled trajectory points meet this criterion (Fig. 8a). The statistical distribution of the positioning errors is shown in the boxplot in Fig. 8b. Here, the box represents the interquartile range (IQR), with its lower and upper edges corresponding to the 25th and 75th percentiles, respectively, encompassing the middle 50% of the data. The upper and lower horizontal lines outside the box respectively indicate the minimum and maximum values within a reasonable range (Li XD and

Fig. 7 Field test for multi-frequency collaborative ISAC in low-altitude UAV detection: (a) diagram of the field setup; (b) UAV with RCS≤0.1 m^2; (c) field test scenario for the mmWave BS; (d) field test scenario for 3.75 GHz BS. VFD: variable frequency drive; RRU: remote radio unit; BBU: baseband unit. References to color refer to the online version of this figure

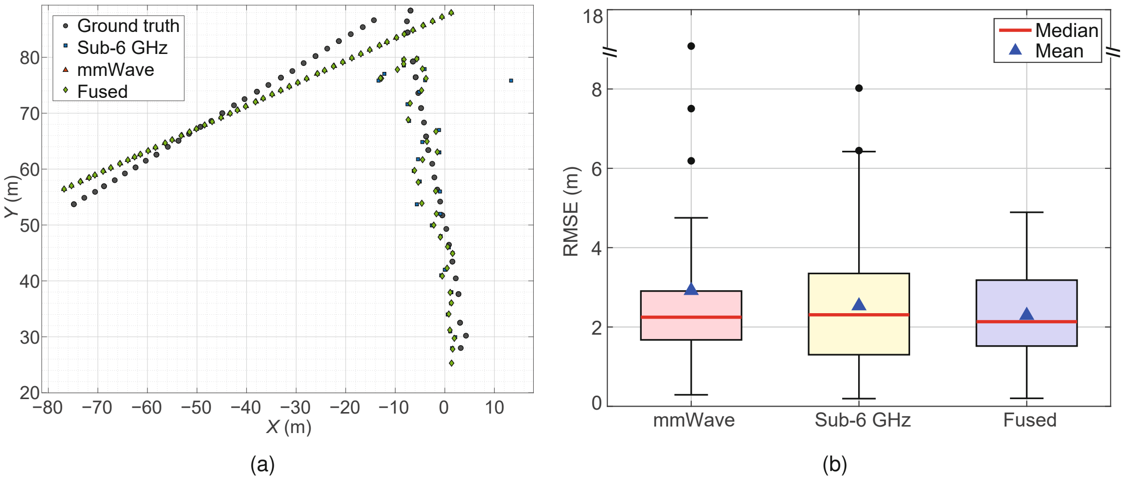


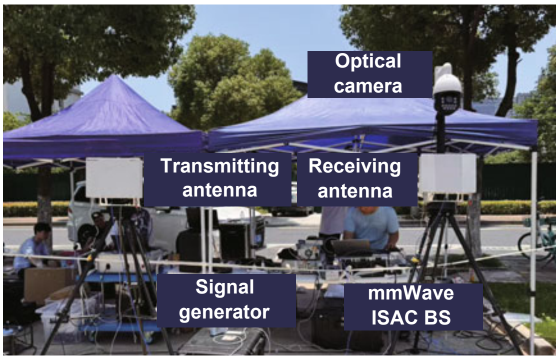
Fig. 8 Positioning performance of multi-frequency ISAC fusion. Trajectory of sensed UAV (a) and sensing accuracy across different frequency bands (b)

Dong, 2025a, 2025b).

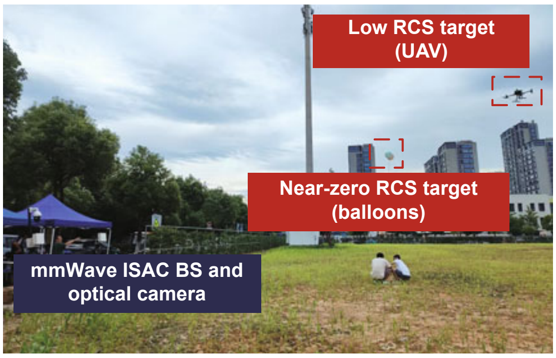
The analysis shows that each method has distinct characteristics. The mmWave approach has the smallest IQR, indicating that its performance is very stable within its effective range. However, it also has the highest RMSE (2.50 m). Together with its lower median, this suggests that while most estimates are accurate, a few larger errors occur, likely due to signal blockage or interference. In comparison, the sub-6 GHz method has a wider IQR, showing that its accuracy varies more than the mmWave method. Its RMSE (2.58 m) is similar to the mmWave result, but its error distribution is more spread out without the same kind of extreme values. The fused method combines the advantages of both. It achieves the lowest RMSE (2.26 m), showing the best overall accuracy, and contains no outliers. By integrating the more uniform error behavior of the sub-6 GHz band, the fused method ensures continuous coverage. This results in an IQR that is slightly wider than that of mmWave alone, but much narrower than that of the sub-6 GHz method. This is a beneficial trade-off: a small loss in consistency is outweighed by clear improvements in accuracy and coverage. These results confirm that the fusion method enhances tracking reliability in complex urban environments, making it suitable for real-world use in low-altitude traffic management, security, and disaster response.

6.3 Case 3: multimodal fusion for ISAC

In a representative low-altitude multi-target sensing task, we deploy a multimodal ISAC sensing platform integrating an mmWave BS and an optical camera, as illustrated in Fig. 9a. The mmWave BS, configured identically to that described in the previous use case, provides all-weather range and velocity measurement capabilities at a refresh rate of 1 Hz. The optical camera delivers high-resolution appearance features and semantic classification information through monocular RGB video streams at 30 Hz. To synchronize the heterogeneous data rates, the system temporally aligns the visual detections with the ISAC cycle by averaging the YOLOv5x outputs over each 1-s interval corresponding to a single ISAC frame. As shown in Fig. 9a, sensors are co-located at the origin of the world coordinate system. The system adopts a heterogeneous processing pipeline based on the synchronized YOLOv5x results and range-Doppler maps, supporting joint detection of typical aerial targets such as UAVs and balloons. The test scene, depicted in Fig. 9b, consists of an open flight area in front of the sensing equipment where a DJI M300 UAV operates. The right rear of the test area is open and free of buildings, while the left rear is occupied by dense structures, creating a heterogeneous background for evaluating sensor performance under different clutter conditions.



(a)



(b)

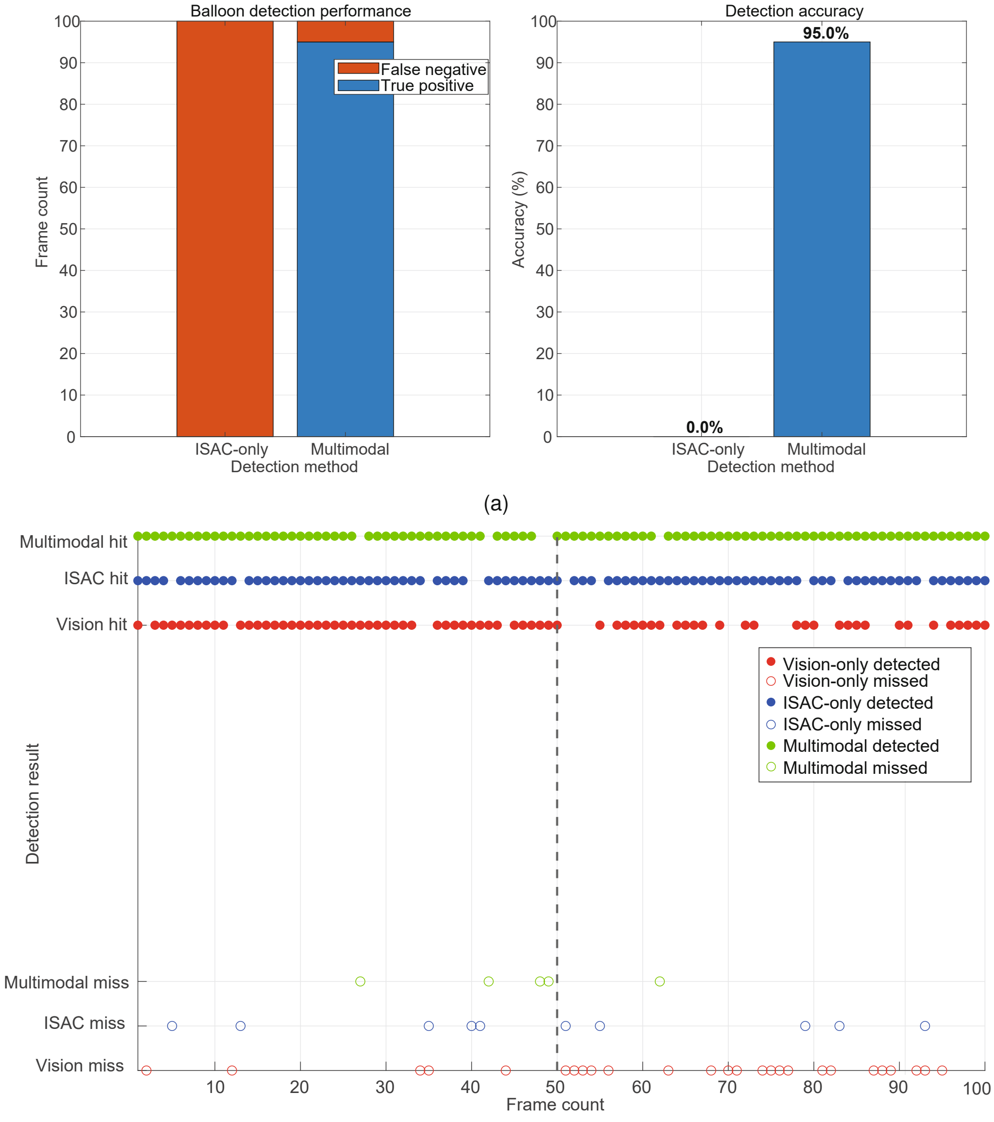
Fig. 9 Diagram of the field setup (a) and field test scenario for mmWave BS and optical camera (b)

In the first scenario, we aim to validate the system's ability to detect the intrusion of a near-zero RCS target, such as a balloon, under multimodal operation. During the UAV's flight, a balloon randomly intrudes into the monitored airspace. Due to its extremely low reflectivity, the ISAC-only sensing mode fails to detect the balloon, triggering no alerts. In contrast, the vision-ISAC fusion mode successfully detects and identifies the UAV and the balloon, generating individual alerts for each target. The incorporation of visual sensors significantly enhances sensitivity to low-RCS objects and is therefore crucial for detecting such objects. This is confirmed by the confusion matrices for balloon detection, as shown in Fig. 10a. The ISAC-only mode results in 0 true positive, whereas the vision-ISAC fusion mode achieves 95, translating to a final detection probability of 95% and conclusively validating the framework's robust target discovery and identification capabilities in low-altitude mixed-target scenarios.

In the second scenario, the UAV flies from the right side of the area to the left. While the right side has an open background where both the camera and the mmWave BS perform effectively, the UAV enters the left region, where building structures in the background severely challenge vision-based tracking. When the UAV moves in front of the building façades, the optical camera fails to maintain tracking as the target visually blends into the cluttered background. However, radar sensing remains unaffected by the visual clutter, and through the fusion system, the UAV continues to be tracked. As shown in Fig. 10b, during the first 50 frames, both vision-only and ISAC-only modes achieve a UAV identification rate of 90%. However, in the subsequent 50 frames where strong background interference is present, the vision-only identification rate drops significantly to 70%, while the ISAC-only mode maintains its 90% accuracy. Crucially, the multimodal fusion approach consistently sustains a high identification rate above 95% throughout the entire sequence. This experiment validates that the multimodal architecture effectively mitigates the limitations of individual sensors, ensuring highly reliable target identification even under visually complex and dynamic conditions.

6.4 Case 4: LAE management platform

The platform's integration within the core network is illustrated in Fig. 11, which details the logical architecture of the dedicated UAV management



(a)

(b)

Fig. 10 Results of target detection: (a) balloon detection; (b) UAV detection

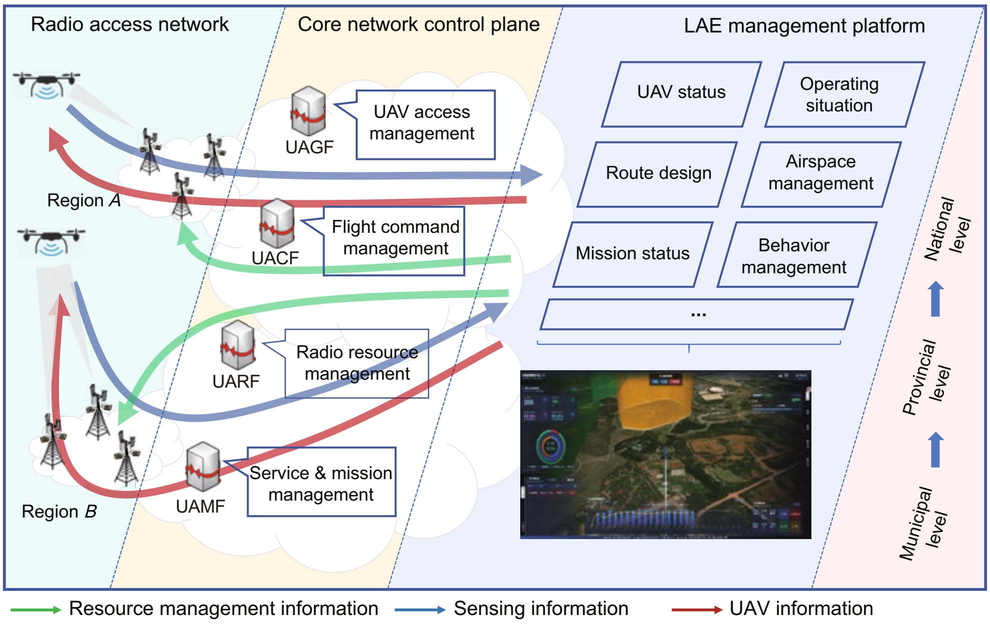


Fig. 11 Logical architecture of the function for the LADIN management platform

functions. This figure zooms into the service and management layer of the broader LADIN architecture, specifying how the platform leverages the core network control plane to govern low-altitude operations. The design follows a clear hierarchical logic: high-level control intents from the LADIN management platform are translated and enforced through a sequence of specialized network functions, including the UAMF for service and mission management, the UACF for flight command management, the UARF for radio resource management, and the UAGF for UAV access management. These functions collectively manage everything from UAV authentication and flight command issuance to radio resource guarantee and seamless handover, establishing a unified access and control channel. This delineation of responsibilities within the core network is fundamental to achieving the deterministic performance and security required for large-scale UAV operations, as demonstrated by the pilot system deployed in Guangzhou, China.

The platform core implements fine-grained airspace and UAV management through dynamic classification of control zones and real-time monitoring of flight behaviors. It supports diverse routing modes, including fixed, dynamic, and free routes, while enabling hierarchical supervision of takeoff and landing sites. A unified visualization interface spanning national, provincial, and district levels provides operators with an integrated view of UAV distribution, mission status, and airspace traffic, allowing interactive management of assets and events. Further extending these capabilities, an intelligent route analysis engine supports both automated and manual planning, equipped with simulation and dynamic risk assessment functions. By continuously evaluating real-time situational data, the system flags anomalies, generates risk maps, and informs policy and path planning. Concurrently, the platform orchestrates regional resources by visualizing and dynamically adjusting airspace configurations and operational boundaries, automatically evaluating impacts and issuing alerts when modifications occur.

Finally, the system integrates meteorological and geographic analysis to visually present environmental effects, from rainfall and wind to terrain and signal propagation. Adopting 3D grid models, it assesses flight suitability to support coordinated operations of large UAV fleets. Together, these functions demonstrate LADIN's closed-loop control paradigm, where sensing drives decision-making, and decisions dynamically reconfigure physical infrastructure to ensure safe, efficient, and scalable low-altitude operations.

7 Conclusions

This paper presents LADIN, a novel architectural framework that holistically integrates CSNC to overcome the limitations of conventional fragmented systems. The core innovation lies in the pervasive infusion of ISAC throughout the three-layer LADIN stack, realized through the following implementations: (1) an OFDM-based waveform design enabling dual-purpose hardware in the infrastructure layer; (2) the construction of a USFS via pluggable back-projection adapters and spatiotemporal modeling in the data fusion layer, offering a coherent and dynamic operational picture; (3) the virtualization of ISAC resources for intent-driven closed-loop control in the service and management layer, where decisions are directly guided by the USFS. Comprehensive validation through a multimodal hardware testbed and field experiments, including multi-frequency collaborative sensing and multimodal fusion for challenging targets, demonstrates that LADIN significantly enhances tracking robustness, improves target identification, and enables seamless airspace governance, establishing a transformative and scalable pathway for future low-altitude digital infrastructure.

Contributors

Jiapeng LI conceptualized the core innovations and drafted the paper. Qixun ZHANG administered the project, acquired the funding, and finalized the paper. Jinglin LI and Dingyou MA supervised the research and provided guidance. Zhiyong FENG provided constructive suggestions and overall direction. Tingyu LI and Jiajun HOU conducted the experiments, performed the testing, and implemented data visualization. All the authors reviewed the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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