Jiapeng LI, Qixun ZHANG, Jinglin LI, Dingyou MA, Zhiyong FENG, Tingyu LI, Jiajun HOU, 2025. Integrated communication–sensing–navigation–control for low-altitude digital-intelligent networks: architecture, enabling technologies, and experimental validation. *Frontiers of Information Technology & Electronic Engineering*, 26(12):2470-2486. https://doi.org/10.1631/FITEE.2500547

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

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

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Research background and challenges

➢ Rapid development of low-altitude economy

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

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➢ Current system challenges

- **Detection failures**

  Low UAV detection rates in urban environments; low-RCS targets are difficult to discover

- **System fragmentation**

  Communication, sensing, navigation, and control systems operate independently.

- **High latency**

  Inter-system communication delays resulting in poor real-time performance

- **Cascade failures**

  Communication disruptions triggering navigation breakdowns

LADIN architecture: three-layer design

➢ Low-altitude digital-intelligent network

A novel architectural framework that, for the first time, establishes an end-to-end integrated communication, sensing, navigation, and control (CSNC) system, transcending the limitations of conventional fragmented systems.

a. Infrastructure layer

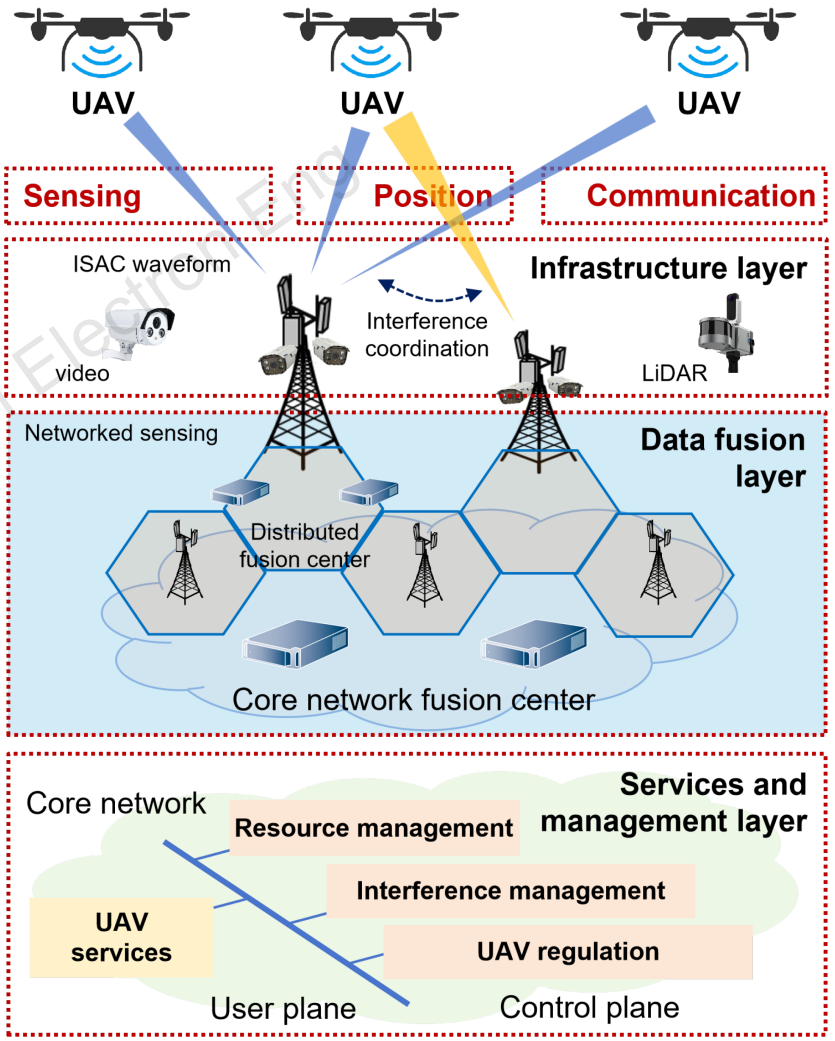
ISAC waveform design with reconfigurable RF front-ends, enabling dual-purpose hardware for simultaneous communication and sensing.

b. Data fusion layer

Constructs USFS via pluggable back-projection adapters and spatiotemporal modeling, integrating ISAC, optical, and LiDAR data.

c. Service & management layer

ISAC resource virtualization for intent-driven, closed-loop control responding to real-time feature space states.



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Infrastructure layer: ISAC waveform design

➢ Core innovation

Through innovative ISAC waveform design and reconfigurable RF front-ends, a single hardware unit simultaneously achieves high-speed data transmission and high-precision environmental sensing.

➢ Multi-dimensional resource allocation

- Time
- Frequency
- Power
- Space

➢ Signal processing

- **Range estimation**

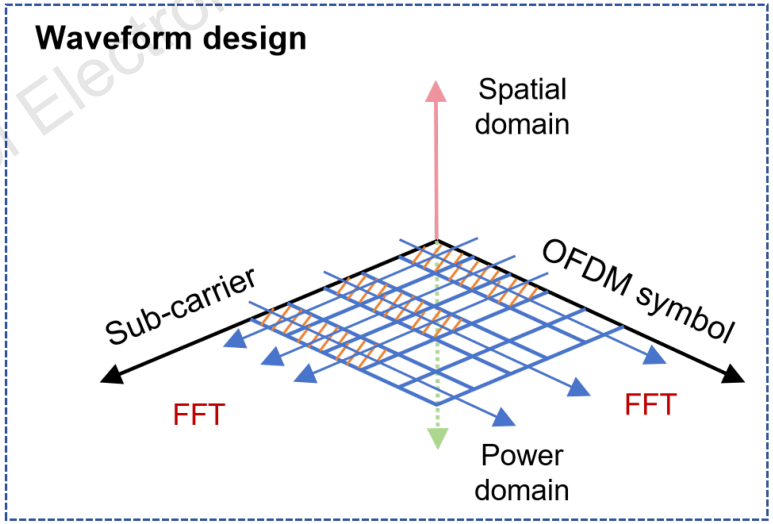
Subcarrier dimension FFT to extract distance information

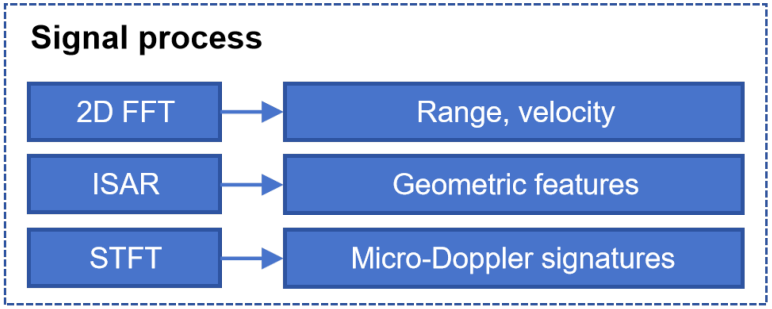
- Velocity estimation

Symbol dimension FFT to extract velocity information

- **High-resolution features**

ISAR imaging and micro-Doppler analysis





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Data fusion layer: unified spatiotemporal feature space

➢ Core challenge & solution

Conventional fusion methods struggle with data-level heterogeneity and association ambiguity. Our approach reframes the challenge as a structured problem of model inversion through pluggable back-projection adapters.

➢ Pluggable back-projection adapters

- **Reverse projection**

Invert observation models to project heterogeneous data into unified multimodal space

- **Modal adapters**

ISAC: signal-to-spatial; Optical: perspective back-projection; LiDAR: geometric sampling

- **Unified space**

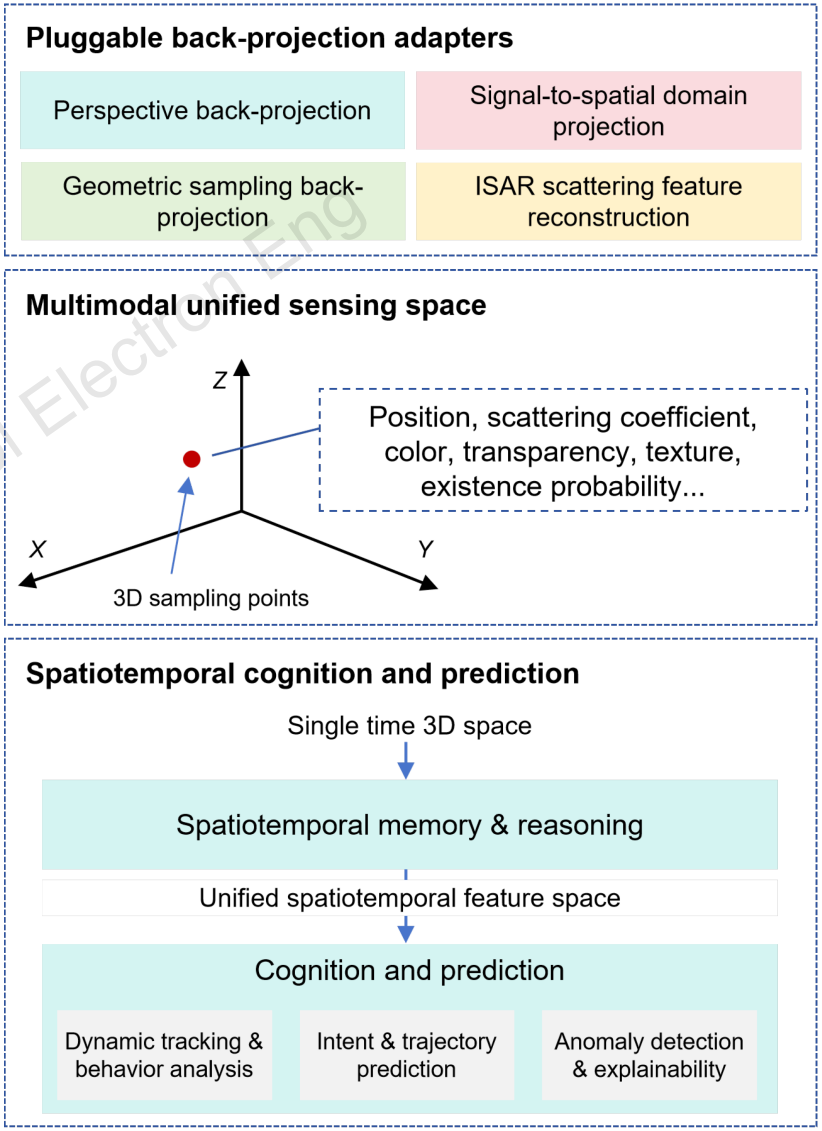
Discretized 3D grid with consistent coordinate system

➢ Spatiotemporal cognition & prediction

Dynamic tracking

Intent prediction

Anomaly detection



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Service & management layer: closed-loop intelligent control

➢ Core function

Transforms USFS situational information into actionable control policies, enabling real-time monitoring and proactive intervention.

➢ CUPS architecture principle

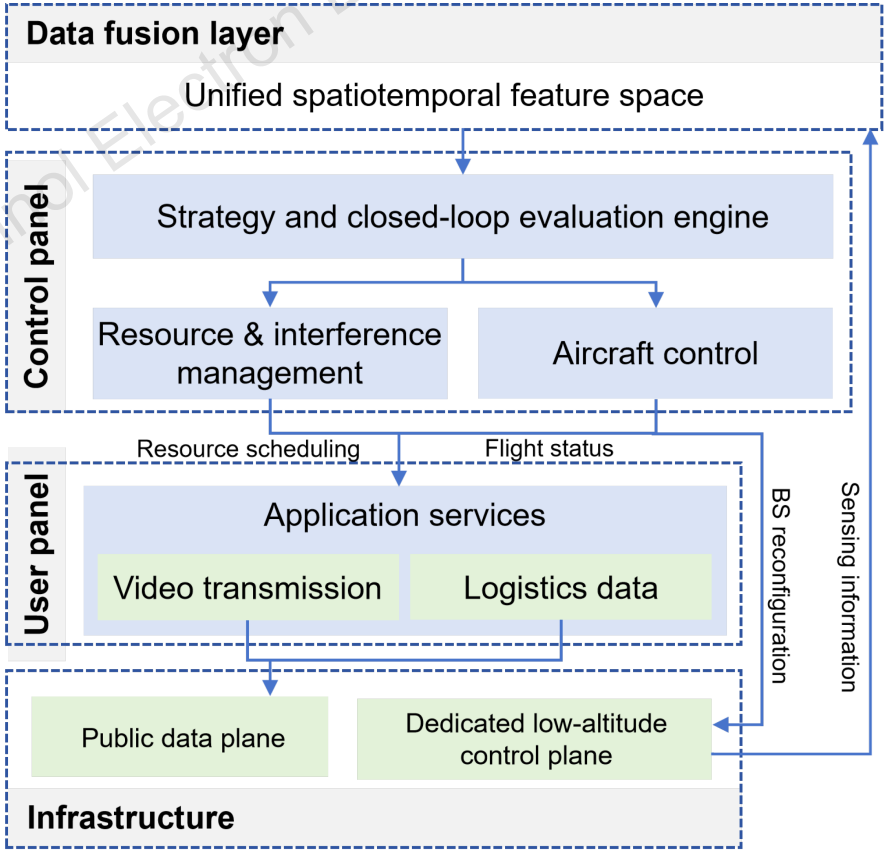
Establishes an independent UAV management network, separate from the public Internet, ensuring deterministic performance for critical functions.

- **Control plane**

Flight commands, conflict resolution, emergency interventions

- **User plane**

Mission data, video transmission, logistics data



➢ Core network functions

UAMF

Service & mission management

UACF

Flight command management

UARF

Radio resource management

UAGF

UAV access management

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Hardware testbed and experimental validation

➢ Multimodal hardware testbed

Platform embodies the three-layer LADIN structure, integrating 5G NR mmWave ISAC and optical vision subsystems via a unified LAN.

ISAC subsystem

26 GHz, 800 MHz BW, 256-element array

Vision subsystem

RGB optical camera, 30 Hz, YOLOv5x

ISAC Validation

Lab validation of OFDM waveform, comparing PDSCH vs DMRS schemes

0.345 m

PDSCH RMSE

Multi-Frequency Sensing

Field test of Sub-6 GHz and mmWave for continuous urban tracking

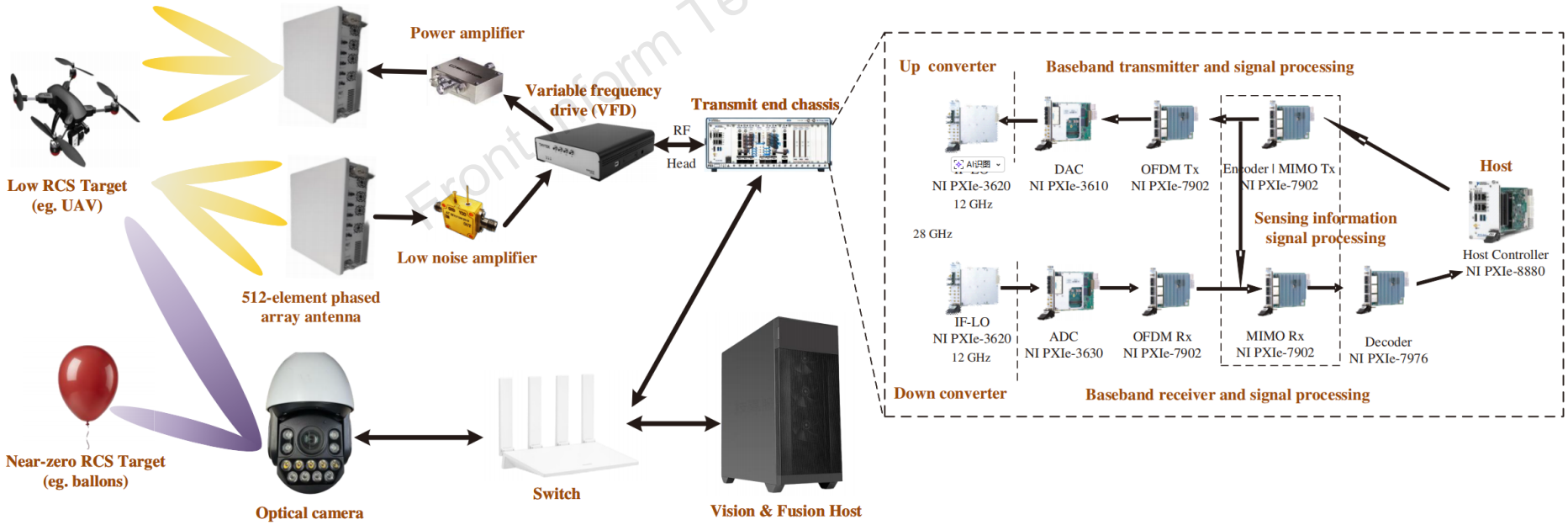
Sub-6 GHz	mmWave
3.75 GHz	26 GHz

Multimodal Fusion

Vision-ISAC fusion for detecting near-zero RCS targets like balloons

ISAC	Fusion
0%	95%

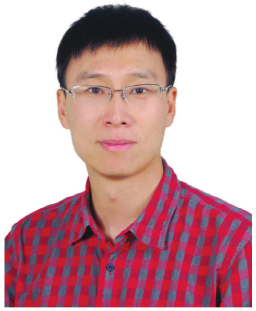
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