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Review

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A review of UAV positioning in LAIN: toward a 5G-core "space−air−ground" integrated and cooperative architecture

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Abstract: The rapid expansion of the low-altitude economy is driving strong demand for highly accurate and reliable positioning technologies to support diverse aerial operations. This review examines core positioning methodologies within the low-altitude intelligent network (LAIN) framework, beginning with an analysis of positioning requirements and performance metrics for low-altitude flight scenarios. It systematically assesses the principles, strengths, and limitations of mainstream positioning systems, including Global Navigation Satellite Systems (GNSS), terrestrial wireless positioning, and autonomous navigation, and it surveys prevalent integrated and cooperative positioning schemes. Our analysis demonstrates that standalone positioning technologies are inadequate in complex low-altitude settings, underscoring the pivotal role of multi-source fusion and unmanned aerial vehicle (UAV) swarm cooperative positioning as future trends. To address infrastructure gaps and high deployment costs in current LAIN systems, we propose a "space−air−ground" integrated and cooperative positioning architecture centered on GNSS and the 5th generation mobile communication technology (5G). The ground layer integrates 5G and GNSS for wide-area enhanced positioning. The aerial layer uses 5G aircraft-to-everything (A2X) and sidelink (SL) communications to build self-organizing networks for cooperative UAV localization. The space layer leverages low Earth orbit (LEO) satellites to overcome coverage limitations in communication and positioning. This hierarchical architecture reduces deployment costs through infrastructure reuse and enables deep integration of communication and navigation capabilities. By supporting collaborative enhancement across all three domains, the framework improves positioning robustness and delivers cost-effective, ubiquitous, and highly reliable positioning services. Finally, we outline promising research directions. This review aims to provide a systematic reference and a novel architectural perspective for the ongoing development of LAIN.

Key words: Low-altitude intelligent network; Unmanned aerial vehicle; Integrated positioning; Integrated communication and navigation; Air−space−ground collaboration

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1 Introduction

In recent years, rapid advances in low-altitude aviation technologies—such as unmanned aerial vehicles (UAVs) and electric vertical takeoff and landing aircraft—have accelerated the global low-altitude economy (LAE), making it a key growth area and a strategic focus for many countries. China has explicitly elevated LAE to a national strategic priority. As low-altitude activities expand, flight operations have become more frequent, increasing demands on safety, efficiency, and intelligent traffic management. The low-altitude intelligent network (LAIN), as the core infrastructure of LAE, plays a critical role in ensuring flight safety. By integrating communication, navigation, surveillance, and meteorological technologies, LAIN enables real-time monitoring, precise positioning, and intelligent scheduling of low-altitude aircraft. Among these capabilities, positioning and navigation systems are particularly essential. High-precision and highly reliable positioning provides accurate location information that supports safe flight in complex low-altitude environments.

Low-altitude flight environments present unique challenges. Urban canyons cause multipath signal interference, electromagnetic noise can degrade signal quality, and adverse weather can induce trajectory deviations. These conditions place greater demands on positioning technologies. Existing methods, such as Global Navigation Satellite System (GNSS), radio-based positioning, Inertial Navigation System (INS), visual localization, and natural-field positioning, each has strengths and limitations in terms of accuracy and reliability. No single positioning technology can meet the diverse and demanding requirements of the LAE. In addition, the current positioning infrastructure is fragmented and lacks sufficient coverage to support large-scale and continuous low-altitude operations. Consequently, many local regions have independently deployed low-altitude navigation networks, leading to redundant construction and inefficient resource use.

To address the challenges of low-altitude UAV positioning and the demand for extensive LAIN deployment, systematic research is needed to improve the robustness of UAV positioning in complex

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low-altitude environments. By analyzing the strengths and weaknesses of current positioning technologies, we can propose solutions that suit the intensive construction of navigation and positioning infrastructure in LAIN. Although several survey studies address UAV positioning, the literature often focuses on visual localization, simultaneous localization and mapping (SLAM), ultra wideband (UWB) positioning, or specific applications such as emergency response and autonomous landing. By contrast, the role of the 5th generation mobile communication technology (5G) in UAV positioning, especially the integration of communication and navigation within LAIN, has received comparatively less attention. Representative survey studies and their focus areas are summarized in Table 1. This work distinguishes itself by concentrating on low-altitude application scenarios and by providing a systematic analysis of mainstream UAV positioning and integrated positioning technologies. Motivated by the anticipated demand for extensive LAIN deployment, we propose a novel space−air−ground integrated and cooperative positioning framework centered on GNSS and 5G. The framework aims to advance the theory of multi-source integrated positioning in complex low-altitude environments and to inform technical planning for LAIN infrastructure.

This study reviews UAV positioning technologies relevant to the LAE, compares their advantages and disadvantages, and argues that GNSS + 5G integrated positioning is a promising solution for low-altitude operations. This paper makes three main contributions:

1. A systematic summary of positioning requirements for UAV operations in low-altitude scenarios.

2. A comprehensive review of existing UAV positioning technologies with a comparative analysis of performance metrics.

3. A novel "space−air−ground" integrated and cooperative positioning architecture centered on GNSS and 5G.

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2 Positioning requirements and applications in LAE

2.1 Positioning requirements in low-altitude activities

Positioning requirements for low-altitude flight activities primarily arise from two sources: regulatory authorities and end users. Regulatory authorities define access requirements for UAVs through standards, specifications, and regulations to ensure safe and orderly low-altitude flights. For example, China's national standard Safety Requirements for Civil Unmanned Aerial Vehicle System (State Administration for Market Regulation and Standardization Administration of the People's Republic of China, 2023) mandates that hovering multirotor UAVs and unmanned helicopters achieve positioning accuracy better than 2 m and landing accuracy better than 5 m. From the user perspective, emphasis lies on flight safety and scenario-specific positioning performance. UAVs must continuously determine their position and status to support flight control and navigation. For precision operations, accurate positioning is required to ensure that flight routes and operational points meet task requirements.

Positioning accuracy requirements vary across flight phases. During cruise, meter-to-submeter accuracy is often acceptable, while takeoff and landing require submeter-to-centimeter accuracy. Requirements also differ by LAE application scenario. Table 2 summarizes positioning metrics and commonly used technologies for four typical application scenarios.

Positioning requirements and technological solutions differ across these scenarios. Logistics transportation demands high precision and low latency. Takeoff, landing, and docking operations require centimeter-level accuracy in confined environments, while route navigation typically relies on submeter accuracy. In dense urban environments, INS and visual localization are integrated to mitigate signal interference and blockage. Agricultural and forestry plant protection emphasizes large-area coverage and cost-effectiveness; meter-level accuracy is generally adequate for uniform spraying, though some tasks require submeter precision. GNSS is the primary technology for broad, remote coverage. Emergency rescue prioritizes reliability and real-time communication in challenging conditions. Where ground-based communication infrastructure is absent, integration with satellite communication becomes crucial; SLAM is used for navigation in complex terrain. Drone aerial displays require coordinated formation flying and visual effects; submeter accuracy (typically GNSS real-time kinematic (RTK)) maintains precise patterns. Visual localization and UWB positioning serve as supplementary technologies to ensure flight safety in GNSS-challenged areas.

2.2 Application scenarios for positioning in LAE

Both precise delivery and collaborative UAV operations depend on high-precision location information. Ground infrastructure management also requires accurate positioning to improve operational efficiency and monitoring. Primary applications of positioning technology in LAE include:

1. Positioning and navigation services for UAVs. High-precision and highly reliable positioning services enable real-time calculation of UAV spatial coordinates. These services provide accurate

Table 1 Overview of UAV localization surveys

Paper	Focus area	Key contributions
Couturier and Akhloufi (2021)	Absolute visual localization	Reviews absolute visual localization, comparing methods by trajectory length, environment size, and error.
Gyagenda et al. (2022)	GNSS-independent navigation	Surveys non-GNSS navigation techniques, analyzing their strengths/weaknesses and fusion approaches.
Xin et al. (2022)	Visual autonomous landing	Summarizes visual landing, covering sensor setups, algorithms, and challenges like lighting/occlusion.
Arafat et al. (2023)	Visual navigation	Reviews visual navigation systems and addresses key challenges (e.g., environmental changes and real-time performance).
Tang P et al. (2024)	Visual detection and navigation for emergency rescue	Reviews visual detection and navigation for UAVs in emergency missions, focusing on real-time and robustness needs.
Gu et al. (2025)	Visual localization	Surveys visual methods (monocular, stereo, SLAM), comparing their accuracy and computational complexity.
Kramarić et al. (2025)	UWB	Surveys short-range localization technologies (UWB), analyzing their accuracy and deployment factors.

Table 2 Comparison of positioning requirements for four typical low-altitude applications

Requirement dimension	Logistics transportation	Agricultural and forestry plant protection	Emergency rescue	Drone aerial display
Sphere of activity	Fixed route	Wide-area farmland/forest area	Disaster scene	Fixed performance airspace
Accuracy	Submeter ~ centimeter level	Meter to submeter level	Meter level	Submeter level
Real-time requirements	High	Medium	High	Extremely high
Cost sensitivity	Medium	High	Low	Medium
Typical solutions	GNSS + INS + Visual	GNSS	GNSS + INS + SLAM	GNSS + visual

three-dimensional coordinates both indoors and outdoors, supporting precise takeoff, landing, and path planning. This capability reduces spatial conflicts with obstacles and improves the efficiency of UAV swarm operations.

2. Operational supervision for management authorities. Positioning technology supplies real-time UAV coordinates, operational status, and trajectory data, preventing air traffic congestion and flight conflicts. When integrated with electronic geofences, the system can automatically detect aircraft that deviate from predefined routes or enter restricted airspace, strengthening LAE supervision.

3. Spatial benchmarks for infrastructure and sensing equipment. Communication, navigation, and surveillance devices within LAIN require high-precision spatial location data to operate effectively. Communication equipment depends on accurate antenna parameters to calculate signal coverage. Both 5G-advanced (5G-A) sensing base station (BS) and radar systems determine UAV positions by computing relative positions between sensor locations and UAVs. High-precision positioning parameters, therefore, improve 5G-A sensing accuracy and radar monitoring performance.

2.3 Performance indicators of low-altitude positioning technology

In complex low-altitude flight scenarios, positioning accuracy is the primary performance metric, followed by coverage, because insufficient coverage can greatly increase hardware deployment costs. Real-time capability and robustness are also critical for reliable positioning services in challenging environments. Cost and power consumption must be considered as they affect UAV economic feasibility and endurance. Drawing on performance indicators used by Arafat et al. (2023) and Kramarić et al. (2025), we evaluate positioning technologies across six dimensions.

1. Accuracy: the difference between the measured position and the true location. Positioning accuracy determines system reliability and usability.

2. Coverage: the spatial extent where the system provides effective positioning. GNSS is global, while some indoor positioning systems are confined to a building.

3. Real-time capability: the ability to update position information rapidly and continuously with low latency, supplying timely data for flight control.

4. Robustness: the capacity to maintain continuous, stable, and accurate service under complex or adverse environmental conditions.

5. Power consumption: electrical power required for system operation, which directly affects UAV endurance and flight time.

6. Cost: total investment for implementing the positioning function, including hardware, software development, and system maintenance, which affects adoption potential.

3 Low-altitude positioning technology

A variety of positioning technologies are available for UAV applications, including GNSS, 5G, UWB, INS, visual localization, SLAM, and geomagnetic positioning. GNSS is the most mature and widely used method. Autonomous methods typically act as supplements in GNSS-denied environments, while 5G and UWB offer native compatibility with communication networks. This section describes the main existing positioning technologies and analyzes their advantages and limitations.

3.1 GNSS

GNSS provides global coverage and continuous, all-weather positioning services for UAVs, and remains the dominant method for low-altitude operations. As shown in Fig. 1, a GNSS receiver determines pseudoranges by receiving signals from multiple satellites and measuring signal propagation times. Using known satellite ephemerides and the principle of range intersection, the system computes the receiver's three-dimensional position. Current GNSS constellations include BeiDou Navigation Satellite System (BDS), Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), and Galileo. Satellite ephemeris errors, ionospheric and tropospheric delays, multipath, and electromagnetic interference limit the accuracy of GNSS single-point positioning (SPP) to about 10 m. To improve accuracy and robustness, enhancement technologies include RTK, precise point positioning (PPP), and low Earth orbit (LEO) satellite-based augmentation.

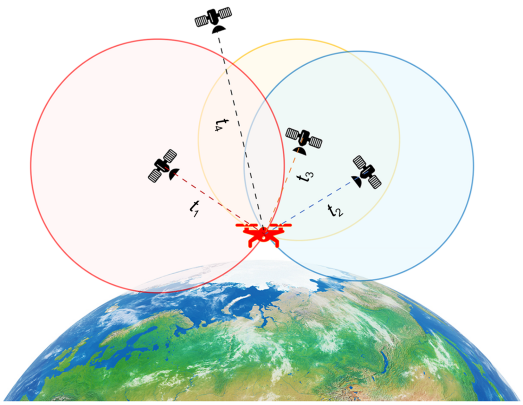

Fig. 1 Schematic diagram of the GNSS positioning principle

3.1.1 RTK and PPP-RTK

RTK uses GNSS carrier-phase differential techniques. It relies on a network of continuously operating reference stations (CORS) to model and mitigate dominant regional positioning errors. These

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errors, as visualized in Fig. 2, primarily include: atmospheric delays and satellite-related inaccuracies. Via a communication network, correction data are transmitted to mobile receivers, enabling real-time centimeter-level positioning accuracy. The RTK positioning principle is illustrated in Fig. 2, and the operational process of RTK is as follows:

1. Each reference station collects satellite observations, such as carrier phase and pseudorange, and transmits raw data to a positioning differential data center (PDDC) in real-time through wired networks.

2. The PDDC builds error models for ionospheric delay, tropospheric delay, satellite clock and orbit errors.

3. The UAV requests differential data, providing its approximate location and user credentials. After verification, the PDDC delivers differential corrections through the communication network.

4. The UAV applies differential processing to its satellite observations using the received corrections to obtain centimeter-level high-precision positioning.

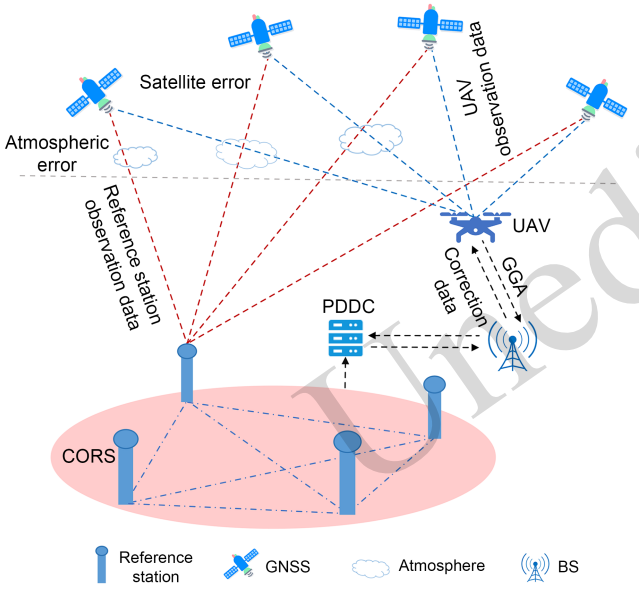

Fig. 2 Schematic diagram of RTK positioning

RTK technology meets high-precision positioning requirements for many low-altitude UAV operations. However, RTK requires building and maintaining CORS networks, which incur high setup and maintenance costs. The broadcast of differential corrections also depends on communications infrastructure; the absence of CORS or communication networks in remote areas limits RTK deployment.

By contrast, PPP does not require a dense CORS network and can achieve submeter-level positioning accuracy. Still, its convergence time is typically on the order of 30 min (Zhang XH et al., 2020), limiting its suitability for some real-time low-altitude flights. PPP-RTK combines the strengths of both methods, offering RTK-like accuracy with reduced dependence on CORS. Although its initialization time limits PPP-RTK for some real-time UAV applications, once converged, it provides continuous centimeter-level positioning as long as satellite tracking is maintained. Therefore, PPP-RTK remains unsuitable for ultra-short-duration, high-maneuverability missions, and for environments with frequent GNSS signal interruptions such as dense forests or super-tall urban canyons.

3.1.2 Pseudolite and LEO satellite technology

Pseudolites simulate satellite signals to improve geometric satellite coverage and provide redundant observations in GNSS-denied areas. Pseudolites can support existing GNSS systems or operate independently. As Tang WJ and Chen (2023) note, pseudolites are not constrained by satellite constellations, can be rapidly deployed, and serve as flexible supplements to maintain continuous positioning services under challenging environments. Due to high deployment costs and limited coverage, pseudolite technology is suitable only for specific low-altitude positioning application scenarios.

Advances in LEO satellite systems offer complementary capabilities. The high dynamics and rapid geometric changes of LEO constellations can compensate for the limitations of medium- and high-Earth-orbit navigation systems in signal-constrained environments, such as urban canyons and mining sites. LEO satellites tend to provide higher received signal power and stronger anti-interference capability, and they can augment GNSS to improve global navigation accuracy and robustness (Tian et al., 2021). LEO satellite augmentation is still maturing, but it has potential for future low-altitude UAV positioning.

3.2 Ground-based wireless positioning

Ground-based wireless positioning technologies include 5G, UWB, WiFi, and Bluetooth. Given the operational range of low-altitude UAVs and the limited coverage of WiFi and Bluetooth, the focus here is on 5G and UWB.

3.2.1 5G

Cellular network positioning estimates the distance or angle between a terminal and a known BS using communication signals. Prior to 5G, cellular positioning accuracy of mobile communications was generally insufficient for many high-precision applications. Advances in 3rd Generation Partnership Project (3GPP) standardization have significantly improved 5G positioning accuracy, as summarized in Table 3. The six primary 5G positioning methods are downlink time difference of arrival (DL-TDOA), uplink TDOA (UL-TDOA), uplink angle of arrival (UL-AoA), downlink angle of departure (DL-AoD), multi-cell round-trip time (Multi-RTT), and enhanced cell ID (E-CID). Their technical principles are illustrated in Fig. 3. In Release 18, 3GPP introduced sidelink (SL) positioning, adding SL positioning reference signals (PRS), so user equipment (UE) can perform ranging and report positioning measurements (3GPP, 2024a; Cha et al., 2025). SL positioning enables mutual communication, ranging, and localization between UEs and applies to scenarios such as the Internet of Vehicles and low-altitude intelligent networks.

China has made significant contributions to mobile communication positioning research. Deng and Yin (2015) proposed a time-coded orthogonal frequency-division multiplexing positioning signal system that superimposes dedicated positioning signals onto communication signals at a power level below the communication system's noise threshold, as shown in Fig. 4. This work led to embedded signal-to-noise positioning techniques and to the 5G co-band PRS concept (3GPP, 2020b). These advances informed international 5G positioning standards and national standards (3GPP, 2020a; 2020b, 2021; State Administration for Market Regulation and Standardization Administration of the People's Republic of China, 2024). With

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Table 3 Evolution of 5G Positioning

Release	Positioning/Enhancement scheme	Target positioning accuracy	Year	Key feature
R16	DL-TDOA/UL-TDOA DL-AoD/UL-AoA Multi-RTT E-CID	Horizontal: 10 m Vertical: 3 m	2020	First systematic definition of the 5G positioning architecture. Introduced 6 in-band positioning techniques with a target accuracy at the meter level.
R17	Mitigating multipath/non-line-of-sight (NLOS) propagation Mitigating timing errors Improve angle measurement accuracy Measurement and communication process optimization	Horizontal: 0.2 m Vertical: 1 m	2022	5G enhancement and expansion. Significantly improved positioning accuracy (submeter level) and efficiency, with enhanced capabilities for Industrial Internet of Things terminals.
R18	SL positioning Low-power high-accuracy positioning RedCap positioning Bandwidth aggregation positioning Carrier-phase positioning Positioning integrity	Centimeter-level	2024	The inaugural version of 5G-Advanced. Supported lower-power positioning terminals and introduced SL positioning technology, targeting centimeter-level accuracy.

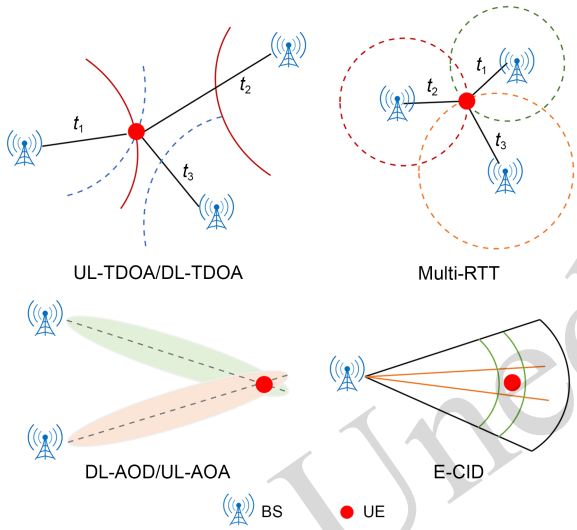

Fig. 3 Schematic diagram of six 5G positioning methods (Jin et al., 2023)

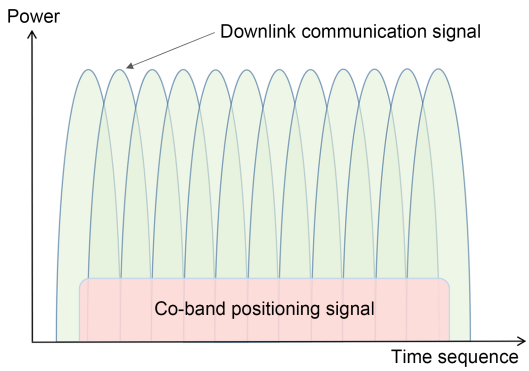

Fig. 4 Schematic diagram of the superimposed spectrum of co-band positioning and communication signals (State Administration for Market Regulation and Standardization Administration of the People's Republic of China, 2024)

standardization and technological maturity, 5G positioning has been deployed in high-precision applications, including indoor environments and industrial parks.

In UAV positioning scenarios, 5G is commonly used for indoor and short-range outdoor positioning and is typically integrated with GNSS for seamless indoor–outdoor coverage, improving accuracy and robustness. 5G supports cooperative positioning among UAV swarms (Gao et al., 2024; Huang Z et al., 2024) and integrates with INS to enhance reliability (Cheng et al., 2023; Mousa et al., 2023; Kabiri et al., 2024). Mousa and Al-Rubaye (2025) further improved the reliability of urban UAV positioning by combining 5G PRS with adaptive deep learning models. By integrating 5G-A sensing, Huang Y et al. (2025) applied sensing techniques to air-ground cooperative UAV positioning.

5G can be deeply integrated with technologies such as GNSS to achieve seamless indoor–outdoor positioning for UAVs. Furthermore, 5G positioning enables cooperative localization for UAV clusters. Despite these strengths, 5G positioning depends on BS infrastructure, which constrains performance in remote or mountainous regions. Insufficient BS coverage or weak signals in these areas can cause positioning failures or degraded accuracy, limiting 5G's ability to provide full coverage independently.

3.2.2 UWB

UWB is a wireless communication technology that transmits extremely narrow pulse signals and is widely used in applications such as the Industrial Internet of Things and intelligent terminals. UWB estimates distance by measuring time-of-flight (ToF) or TDOA, and combines measurements from multiple BS to compute positions. A typical UWB positioning system includes multiple positioning BS and mobile tags. Tags measure ToF/TDOA through wireless signal exchanges with the BS and compute coordinates using positioning algorithms.

UWB's high time resolution yields minimal ranging error under line-of-sight conditions. However, UWB faces barriers to large-scale deployment, including high setup costs, susceptibility to environmental interference, relatively high power consumption, and the limited coverage range of a single BS. Currently, UWB finds two main UAV applications: (1) indoor or short-range UAV localization (You et al., 2020; Xiang et al., 2025); (2) collaborative positioning within UAV swarms, where UWB supports inter-UAV ranging and information sharing to improve swarm-level positioning accuracy (Nouali et al., 2022; Vital and Ramos, 2025). UWB is also commonly fused with GNSS to improve UAV positioning accuracy and reliability (Qi et al., 2020; Zhang SN et al., 2024).

3.3 Autonomous positioning

Autonomous positioning technologies allow UAVs to estimate their position in real time using onboard sensors and algorithms

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without relying on external positioning systems. The main types include INS, visual localization, SLAM, and geomagnetic positioning.

3.3.1 INS

An INS is an autonomous navigation technology commonly integrated with GNSS. INS operates independently of external signals by measuring acceleration and angular velocity with accelerometers and gyroscopes and integrating these measurements to estimate position, velocity, and attitude. The typical process includes: (1) measuring acceleration and integrating it twice to obtain displacement; (2) updating the attitude matrix from gyroscope angular rates; (3) transforming navigation frame motion into a global coordinate frame to derive the carrier's motion parameters and position.

INS offers strong autonomy, good concealment, high short-term accuracy, and immunity to external signal outages. It is particularly suitable for short-term UAV positioning when GNSS is unavailable or degraded. To reduce error accumulation, INS is commonly fused with other positioning technologies such as GNSS (Elamin et al., 2022; Niu et al., 2024; Zhang H et al., 2024), UWB (Meng et al., 2023), and visual localization (Dong J et al., 2022; Xiong et al., 2024).

3.3.2 Visual localization

Visual localization acquires environmental images using cameras or other visual sensors and applies computer vision algorithms to extract and match features, thereby estimating the system's position or the position of target objects. It offers advantages of low cost, high positioning accuracy, and ease of integration (Ye HQ et al., 2024), operating independently of GNSS. Visual localization can be fused with INS and LiDAR, and is widely used in applications such as autonomous driving and UAV navigation.

Visual methods are sensitive to lighting and environmental changes (Wang TY et al., 2024) and require substantial storage and computational resources (Yang LW et al., 2022; Ye HQ et al., 2024). Sensor fusion improves positioning accuracy and robustness. Deep learning techniques enable richer feature representations and enhanced visual localization performance (He MF et al., 2024; Zhao H et al., 2024). In many LAE scenarios, UAV storage and compute resources are limited; lightweight, self-supervised approaches can mitigate this constraint (Qu et al., 2025).

3.3.3 SLAM

SLAM estimates a system's position in real time while building a map of the environment. SLAM uses sensors to collect environmental data and enables autonomous navigation and obstacle avoidance through feature extraction, pose estimation, and map construction. It is widely used in UAV navigation and positioning due to its real-time capabilities, adaptability, and autonomy.

SLAM approaches are commonly categorized by sensor modality into laser SLAM and visual SLAM. Laser SLAM uses LiDAR sensors to produce high-precision point clouds and typically achieves high positioning accuracy, but LiDAR systems are bulky and costly and provide relatively limited sensing information. Visual SLAM relies on cameras as the main sensors, which are compact and low-power while providing rich environmental information, though performance depends heavily on scene texture and lighting. SLAM is primarily used for high-precision autonomous localization and navigation in GNSS-denied environments: It supports centimeter-level hovering control (Li ZY et al., 2024), obstacle avoidance (Chen C et al., 2022), and can maintain positioning accuracy within about 1.5 m during long-distance flights (Li DD et al., 2023).

3.3.4 Geomagnetic positioning

Geomagnetic positioning exploits spatial variations in the Earth's magnetic field. A geomagnetic positioning system measures local magnetic field vectors with magnetometers and matches them to a pre-established geomagnetic map to determine position. For UAVs, onboard magnetometers record geomagnetic field data along the flight path; distinctive field features are then matched to a stored geomagnetic field model or an anomaly map to provide real-time localization.

Geomagnetic positioning requires no artificial signal sources and thus offers strong concealment and passive operation. However, magnetic measurements are susceptible to local metallic objects and electromagnetic sources. In regions with low geomagnetic variation, positioning errors can range from several meters to tens of meters, limiting their suitability for high-precision applications. For this reason, geomagnetic positioning is typically used as an auxiliary method and fused with visual or inertial sensors to improve overall reliability (Chen K et al., 2021; Hu et al., 2021).

This section has introduced four mainstream autonomous positioning technologies for UAVs: INS, visual localization, SLAM, and geomagnetic positioning. Each technology can provide positioning in GNSS-denied environments but differs in accuracy, environmental dependence, and cost, making it difficult for any single method to independently meet the full-cycle, high-reliability positioning demands of complex low-altitude scenarios. INS delivers strong short-term accuracy but accumulates errors over time. Visual localization and SLAM provide rich perception and high relative accuracy but depend on environmental texture and lighting, and impose high computational loads. Geomagnetic positioning is passive and concealed but sensitive to electromagnetic interference and offers limited spatial discriminability. Therefore, multi-source fusion is necessary to balance accuracy, robustness, and practicality on resource-constrained UAV platforms.

3.4 Comparison of localization approaches

The technologies discussed above have distinct strengths and limitations across accuracy, cost, and coverage, summarized in Table 4. GNSS (including RTK and PPP-RTK) is a mature solution that provides centimeter-level accuracy in open airspace and across the globe. Its signals, however, are vulnerable to obstruction and interference. RTK requires a costly ground-based augmentation network; PPP-RTK has relatively long convergence times; pseudolite positioning offers limited coverage at high cost; LEO-based positioning is still maturing. 5G positioning leverages communication infrastructure to achieve high accuracy and reduce the need for dedicated positioning equipment. This makes 5G attractive as a wide-area high-precision solution that complements GNSS signal coverage gaps in indoor, underground, and other challenging environments. UWB offers centimeter-level accuracy but requires dense BS deployment due to limited coverage, limiting it to confined-area positioning scenarios. INS provides high autonomy and excellent short-term accuracy, but suffers cumulative error, and high-precision inertial measurement units (IMUs) are expensive. Visual positioning uses

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low-cost cameras to deliver centimeter- to meter-level accuracy with rich environmental sensing; it depends on lighting and requires high computational power. SLAM enables real-time mapping and localization in unknown environments: Laser SLAM can achieve centimeter-level accuracy at a higher cost. At the same time, visual SLAM is more affordable but computationally intensive and sensitive to dynamic scenes. Geomagnetic positioning provides passive localization but is susceptible to local disturbances and depends on high-precision geomagnetic maps.

Overall, GNSS offers clear advantages for wide-area spatial positioning, while other positioning technologies contribute complementary capabilities. No single positioning technique satisfies all requirements for complex low-altitude operations; therefore, practical systems should integrate multiple technologies. In open-air outdoor operations, GNSS typically serves as the primary solution, supplemented by INS to mitigate short-term outages. When higher precision is needed near structures or complex terrain, visual localization or laser SLAM can be incorporated. In unknown environments that require on-the-fly mapping, SLAM-based positioning is appropriate. Indoors, alternative technologies such as 5G, UWB, or SLAM provide the primary localization solution.

4 Integrated positioning

Accurate positioning and navigation are essential for stable UAV flight during aerial operations. As shown in Section 3, each positioning technology has distinct strengths and limitations, so relying on a single method cannot guarantee flight safety across all scenarios. Consequently, multi-sensor data acquisition and fusion are used to improve positioning accuracy and reliability. This section summarizes and analyzes representative fusion and cooperative positioning schemes.

4.1 GNSS + INS

The combination of GNSS and INS is the most widely adopted solution for UAV positioning. GNSS provides absolute location information but is vulnerable to signal blockage and spoofing. INS operates independently of external signals and delivers high short-term measurement accuracy, but its errors accumulate over time due to integration drift. Integrating GNSS and INS captures complementary advantages, improving accuracy, continuity, and resistance to interference (Wang L et al., 2024). Fig. 5 illustrates a typical GNSS/INS integrated architecture. Depending on the integration level, GNSS + INS fusion is typically classified as loose, tight, or deep coupling. Kalman filtering remains the most widely used integration method (Boguspayev et al., 2023).

Early work emphasized loosely coupled foundational frameworks. Wang GQ et al. (2018) developed a GNSS/INS loosely coupled system using Kalman filtering for agricultural UAVs, correcting INS drift with GNSS updates; the approach degraded when satellite signals were rejected. Jiang et al. (2021) proposed an extended state observer to improve the loose-coupling performance of low-cost sensors by precisely modeling measurement noise. Still,

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Table 4 Comparison of performance indicators of main low-altitude positioning technologies

Positioning technology		Accuracy	Coverage	Real-time capability	Robustness	Power consumption	Cost
GNSS		SPP: ~10 m RTK: Centimeter level	PPP: Global RTK: Wide	PPP: Low RTK: High	Medium	Medium	Low
5G		Centimeter level	Wide	High	High	Medium	Low
UWB		Centimeter level	Small-scale	High	Medium	Medium	High
INS		Centimeter level (short-term)	Unrestricted	High	High	Medium	MEMS: low Precise: high
Visual localization		Submeter to meter level	Unrestricted	Medium	Medium	High	Medium
SLAM	Laser SLAM	Centimeter level	Unrestricted	High	High	High	High
	Visual SLAM	Submeter to meter level	Unrestricted	Medium	Medium	Medium	Medium
Geomagnetic positioning		Meter level	Global	Medium	Medium	Low	Low

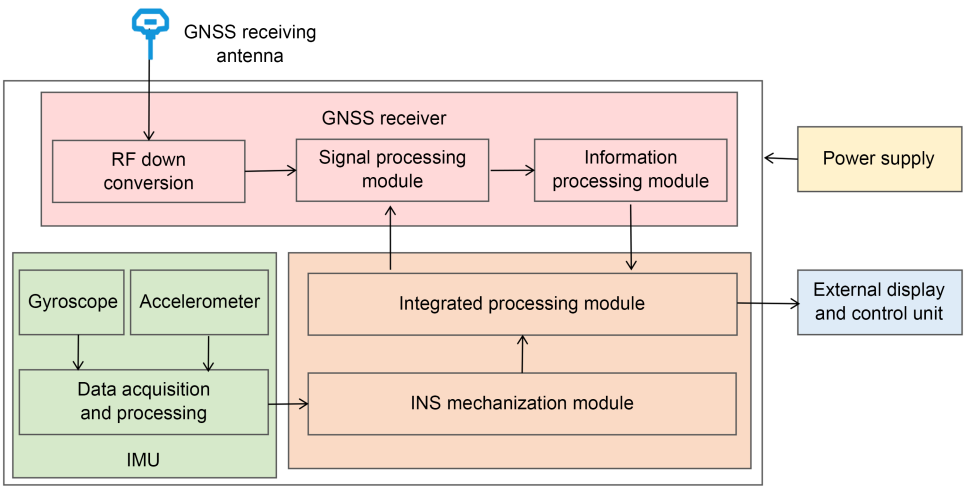

Fig. 5 Structure diagram of GNSS/INS integrated positioning

performance remained constrained in sparse-signal environments such as urban canyons. To address these limitations, tight-coupling approaches gained traction. Dong Y et al. (2020) fused pseudorange, Doppler, and carrier-phase data via robust sequential Kalman filtering to suppress dynamic interference in urban environments. Sun et al. (2020) introduced an integrity monitoring module and enforced UAV no-fly zones by analyzing Kalman innovations. Song Y and Hsu (2021) used factor-graph optimization in a tightly coupled framework, reformulating navigation as a nonlinear least-squares problem to improve localization robustness in indoor multipath environments. Wang H et al. (2022) proposed a clustering-based multipath/non-line-of-sight (NLOS) detection method to optimize GNSS observation weighting, thereby enhancing tightly coupled performance in urban areas.

Recent advancements in deep coupling technology have yielded further gains. Zheng et al. (2024) introduced a full-process prediction model with multi-level threshold discrimination to improve carrier-phase tracking continuity under obstruction. Feng et al. (2025) proposed a noise-adaptive fusion framework with dual noise estimation, reporting a 36.71% improvement in localization consistency for unstructured environments.

4.2 GNSS + 5G

With improvements in 5G positioning accuracy and network coverage, 5G can serve both as an independent wide-area positioning technology and as a complement to GNSS in occluded environments. Integrating GNSS and 5G can produce ubiquitous, high-precision positioning services. 5G-assisted GNSS shortens convergence time; constructing CORS-like services using 5G BS can reduce the cost of CORS deployment and maintenance, and 5G provides stable network transmission for RTK differential information (Jin et al., 2023). GNSS + 5G integration leverages multi-source observation fusion, filtering algorithms, and scenario-adaptive strategies to enhance positioning accuracy, continuity, and reliability in complex environments, such as urban canyons and indoor spaces.

Research on GNSS and 5G integration has progressed along two main directions: system architecture and filtering algorithms. Early work focused on architectural design. Yin et al. (2018) proposed a GNSS/5G integration method leveraging device-to-device (D2D) communication, establishing a foundational framework. Tong et al. (2021) developed an integrated BDS and self-organizing network framework, and Liu JR et al. (2023) proposed a joint positioning scheme based on a dependable spatiotemporal network to enhance system robustness. Later efforts emphasize algorithmic optimization. Bai et al. (2022) proposed a multi-rate adaptive Kalman filter; Zhang W et al. (2023) developed a resilient observation model; Guo G et al. (2024) and Jiao et al. (2024) introduced adaptive-step Kalman filtering and weighted robust iterative Kalman filtering, respectively, improving positioning stability in complex environments. Recent work shows a trend toward tightly coupled multi-source fusion. Song WW et al. (2025) validated a tightly coupled GNSS/5G fusion method on a smartphone platform in urban, occluded environments. Deng et al. (2025) extended this approach by adding an IMU to form a tightly coupled GNSS + 5G + IMU framework, achieving dynamic positioning accuracy of 0.83 meters.

4.3 GNSS + visual localization

Visual localization uses onboard cameras to detect ground features for position estimation, and is particularly valuable in GNSS-denied conditions. Fusing GNSS with visual systems combines absolute position constraints from GNSS to suppress visual-inertial odometry drift, while continuous relative tracking from visual sensors is used when fewer than four satellites are available. Tightly coupled fusion typically merges visual pose increments with GNSS observations.

Baldoni et al. (2020) proposed a hybrid, switchable framework that toggles between loose and tight coupling, offering design flexibility, though threshold-based switching can introduce instability. Cao et al. (2022) developed the GVINS system, which tightly couples GNSS, visual, and IMU data via nonlinear optimization and provides an online coarse-to-fine initialization to align local and global coordinate systems. Li XW et al. (2024) used an optimization-based approach to improve robustness in urban environments. Dai et al. (2024) addressed scale uncertainty in monocular vision for GNSS-denied environments, such as tunnels, thereby extending the applicability of visual methods.

4.4 GNSS + UWB

GNSS + UWB fusion combines satellite global coverage with UWB's high-precision ranging capability. Kalman and federated filters enable seamless indoor−outdoor positioning and improve accuracy and continuity in occluded or multipath-prone environments, making this combination suitable for UAVs.

Research focuses on NLOS mitigation, time synchronization, and optimal multi-source fusion. After early feasibility demonstrations by Opshaug and Enge (2002), studies shifted to algorithmic optimization. Zhuang et al. (2021) fused GNSS carrier phase with UWB ranging to reach centimeter-level accuracy, though UWB-specific NLOS errors remained an issue. Luo et al. (2024) used IMU data to compensate for NLOS errors in a GNSS + UWB + IMU tight-coupling scheme. Yao HL et al. (2025) combined UWB ranging with angle of arrival (AoA) to detect and mitigate NLOS conditions. Lv et al. (2025) designed an adaptive Kalman filter to adjust measurement variances in NLOS conditions dynamically. Guo YH et al. (2023) improved time synchronization using an enhanced extended Kalman filter. In robust estimation work, Yan et al. (2024) applied Helmert variance-component estimation to optimize observation weighting, and Zhang D et al. (2025) improved single-epoch positioning accuracy by integrating RTK with weighted linear regression of UWB observations.

4.5 Other integrated positioning

Fusing three or more technologies further enhances positioning accuracy and robustness. Typical combinations integrate GNSS, inertial sensors, and additional modalities to deliver reliable, high-precision positioning solutions across environments. In GNSS + INS + UWB integration, Yao LH et al. (2024) used a federated filter to enable seamless indoor−outdoor positioning with horizontal errors below 10 cm. However, the layered fusion structure showed limited adaptability in highly dynamic scenarios. Zhao JG et al. (2025) introduced multiple fading factors and an adaptive cost function within a tightly coupled framework to enhance the robustness of

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cooperative vehicle positioning in NLOS environments, at the expense of increased system complexity. For GNSS + SINS + Vision, Liu A et al. (2024) dynamically adjusted multi-source weight ratios using an adaptive filter to suppress abnormal measurements; Ye T et al. (2025) fused point and line features to reduce positioning errors in GNSS-degraded environments, albeit at increased computational cost. These studies show that multi-source fusion provides complementary benefits but increases system complexity and computational demand; improving algorithmic efficiency while preserving accuracy is a key research challenge.

4.6 Cooperative positioning

Integrated multi-sensor solutions enhance localization but increase cost and complexity. Cooperative positioning leverages inter-agent information exchange and collaboration to reduce infrastructure dependency while maintaining or improving positioning performance, making it attractive for complex environments and large-scale tasks. Cooperative positioning involves multiple devices sharing measurements, position estimates, and environmental data, and combining them using collaborative algorithms to improve the positioning accuracy, availability, and robustness of nodes within a network. The concept dates to Kurazume et al. (1996), originally in mobile robotics.

In UAV swarms, cooperative positioning reduces reliance on a central node by enabling intra-swarm status sharing. One representative method is block-based multidimensional scaling, which divides large clusters into blocks to reduce computational load. During formation flights, UAVs measure inter-UAV distances and angles and fuse this data with their own observations for more accurate formation control and path planning. This approach exploits collective information to handle navigation challenges in complex settings but requires robust communications and advanced data fusion algorithms.

Research on cooperative UAV positioning has progressed from architecture proposals to focused algorithmic and application studies. Chen R et al. (2021) proposed a distributed cooperative localization framework. Algorithmic advances include information-geometry-based fusion (Tang CK et al., 2022), manifold gradient filtering for hybrid UAV-wireless sensor networks (Song Z et al., 2024a), and wide-area cooperative algorithms (Song Z et al., 2024b). Application-oriented work includes a lightweight follower−motion−vector localization for leader−follower formations (Zhu et al., 2022) and spoofing detection and mitigation mechanisms (Bi et al., 2024). Despite progress, balancing communication reliability, fusion complexity, synchronization, and cybersecurity remains a core challenge.

4.7 Summary

This section reviews integrated and cooperative positioning schemes for low-altitude UAVs. As LAE scenarios become more complex, UAV positioning technology has shifted from single-technique solutions to multi-source integration and cooperative approaches. As illustrated in Fig. 6, integrated positioning fuses two or more sources using Kalman filtering, graph optimization, or other estimation methods, and adapts strategies according to context to exploit complementary strengths. Cooperative positioning extends this idea to multiple agents, improving swarm-level accuracy and fault tolerance via information sharing and collaborative algorithms. A multi-agent framework can also augment the cooperative perception and

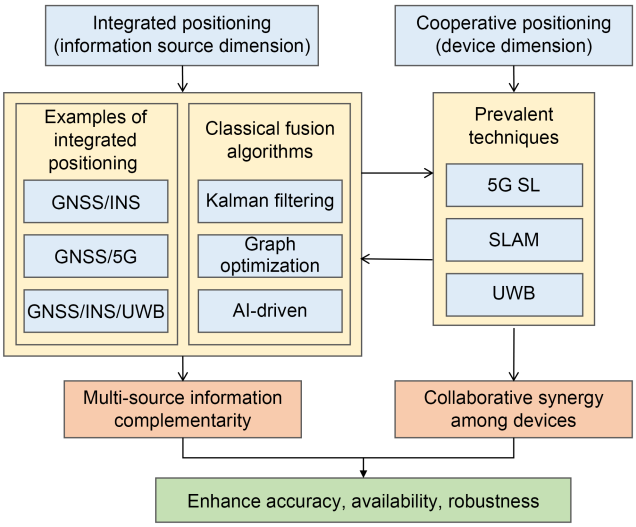

Fig. 6 Schematic diagram of the relationship between integrated positioning and cooperative positioning

decision-making capabilities of UAVs, improving operational robustness in complex environments (Fan et al., 2024).

Multi-source integrated positioning enhances a single-UAV's capabilities by combining heterogeneous sensors and leveraging their complementary strengths; this approach addresses limitations in accuracy, continuity, and reliability, enabling seamless high-precision positioning across broad outdoor areas to confined indoor spaces. Table 5 summarizes the comparative advantages and limitations of common integrated schemes. GNSS + INS provides the foundational approach, and loose, tight, and deep coupling offer different trade-offs between complexity and performance. GNSS + 5G leverages 5G's extensive coverage and high precision to build wide-area indoor−outdoor services. GNSS + visual methods address drift and scale ambiguity via combined features and adaptive filtering. GNSS + UWB enables seamless indoor−outdoor centimeter-level positioning, though UWB deployment cost and NLOS remain concerns. Multi-source fusion improves capability at the cost of increased system complexity and computational burden.

Cooperative positioning extends localization from single UAVs to entire swarms, enabling "swarm intelligence" via shared information. This reduces reliance on single-node accuracy and external infrastructure and supports large-scale, cost-effective, robust cooperative operations of UAV swarms. Challenges include communication reliability, fusion complexity, synchronization load (Fan and Wang, 2025), and cybersecurity risks.

5 Integrated and cooperative positioning for LAIN

The preceding analysis shows that no single low-altitude positioning method can meet the stringent requirements for high reliability and precision in complex low-altitude operations. Vulnerabilities such as GNSS signal loss in obstructed areas, INS drift, the limited range of visual and UWB solutions, and the reliance on 5G infrastructure make standalone deployment impractical. Consequently, multi-source integrated positioning and cooperative positioning are

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Table 5 Comparative analysis of integrated positioning schemes for low-altitude UAVs

Integrated schemes	Advantage	Disadvantage	Paper
GNSS + INS	- Complementary advantages in accuracy and reliability - Enhanced anti-spoofing and anti-interference capability	- INS errors accumulate over time - Deep coupling is challenging to implement	Wang GQ et al., 2018; Dong Y et al., 2020; Sun et al., 2020; Jiang et al., 2021; Song Y and Hsu, 2021; Wang H et al., 2022; Zheng et al., 2024; Feng et al., 2025
GNSS + 5G	- Enables ubiquitous high-precision positioning services - Reduces CORS infrastructure deployment and maintenance costs	- Dependent on 5G BS coverage - Challenges with multi-source signal stability - Positioning in urban canyons still requires optimization	Yin et al., 2018; Tong et al., 2021; Bai et al., 2022; Liu JR et al., 2023; Zhang W et al., 2023; Guo G et al., 2024; Jiao et al., 2024; Deng et al., 2025; Song WW et al., 2025
GNSS + Visual	- Absolute position constraints suppress visual-inertial odometry drift - Improves continuity in complex environments	- Complex initialization for coordinate system alignment - Difficult feature extraction in low-texture environments	Baldoni et al., 2020; Cao et al., 2022; Dai et al., 2024; Li XW et al., 2024
GNSS + UWB	- Seamless indoor−outdoor positioning - Centimeter-level accuracy	- High deployment cost for UWB BS - NLOS errors impact accuracy	Opshaug and Enge, 2002; Zhuang et al., 2021; Guo YH et al., 2023; Luo et al., 2024; Yan et al., 2024; Lv et al., 2025; Yao HL et al., 2025; Zhang D et al., 2025
GNSS + INS + visual	- Suppresses INS drift and visual scale ambiguity simultaneously - Enhances robustness in degraded GNSS or low-texture scenes	- High computational load from visual processing - Complex sensor calibration and initialization - Performance depends on environmental texture and lighting	Liu A et al., 2024; Ye T et al., 2025
GNSS + INS + UWB	- Seamless indoor−outdoor positioning capability - High robustness in NLOS environments	- High system integration complexity and cost - Performance degradation in dense NLOS settings	Yao LH et al., 2024; Zhao JG et al., 2025
Cooperative Positioning	- Reduces dependence on single-node accuracy and infrastructure - Enhances overall swarm fault tolerance - Suitable for large-scale swarm operations	- High demands on communication reliability - Complex data fusion and network synchronization - Security vulnerabilities	Chen R et al., 2021; Tang CK et al., 2022; Zhu et al., 2022; Bi et al., 2024; Song Z et al., 2024a, 2024b

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essential to improve the accuracy and robustness of UAV navigation. Among the integrated strategies, GNSS + 5G fusion stands out as an auspicious approach. These technologies complement one another in coverage and accuracy, and their deep integration enables a unified low-altitude communication and positioning network. By leveraging existing 5G BS infrastructure to support GNSS positioning functions, this approach can substantially reduce the construction and operational costs associated with dedicated navigation networks such as CORS, thereby facilitating scalable LAIN development. We therefore propose a novel framework for integrated and cooperative positioning based on GNSS + 5G fusion that envisions a space−air−ground integrated system to support efficient and reliable LAE operations.

5.1 Low-altitude "space−air−ground" integrated and cooperative positioning scheme

LAIN provides the spatiotemporal foundation for low-altitude economic activities: Its communication network enables data exchange, its surveillance network supports detection and tracking, and its navigation network provides high-precision three-dimensional positioning. The current LAIN infrastructure remains incomplete, technology choices are fragmented, and construction and operational costs are high. Gaps include communication blind spots in portions of low-altitude airspace, costly radars that struggle to detect "low−slow−small" aircraft, extensive CORS deployment requirements for high-precision GNSS, and added complexity when integrating INS, visual localization, and SLAM in GNSS-denied environments. Constructing communication, navigation, and surveillance networks independently risks redundant infrastructure and wasted resources.

As of October 2025, China had deployed over 4.7 million 5G BS. If high-precision positioning can be delivered over these networks, they can compensate for GNSS coverage blind spots indoors, underground, and in other constrained areas, and can synergize with GNSS to provide ubiquitous, seamless spatiotemporal information for the LAE. 5G positioning offers high accuracy, broad coverage, mature standards, and relatively low incremental cost, and it complements GNSS well. With advances in 5G positioning, 5G-GNSS integrated communication and navigation (ICAN), 5G-A integrated sensing and communication (ISAC), the emerging 6G era, and LEO satellite systems, it is feasible to use communication facilities as the backbone for an integrated communication, navigation, and sensing (CNS) service in LAIN.

Accordingly, we propose a "space−air−ground" integrated and cooperative positioning scheme for LAIN, shown in Fig. 7. The solution is built on 5G communication infrastructure. By reusing sites, power, data centers, and spectrum, and by sharing hardware and backhaul resources, the architecture integrates "CNS" functions and avoids redundant network construction. Table 6 summarizes components and functions. The architecture centers on 5G networks and GNSS and incorporates 5G aircraft-to-everything (A2X) communication, 5G SL cooperative positioning, and LEO satellites as complementary elements to form an integrated space−air−ground positioning augmentation framework.

1. Ground CNS: Based on the 5G + GNSS ICAN solution (Section 5.2), this layer improves low-altitude positioning accuracy and robustness while reducing the construction and maintenance cost of CORS stations.

2. Air ICAN: Using 5G A2X/D2D and 5G SL technology to establish direct communication links and relative positioning within UAV clusters (Section 5.3), this layer supports submeter-level relative position awareness for formation flight and obstacle avoidance.

3. Space ICAN: Integrating LEO satellites, BDS short-message services, and future 6G capabilities with next-generation GNSS

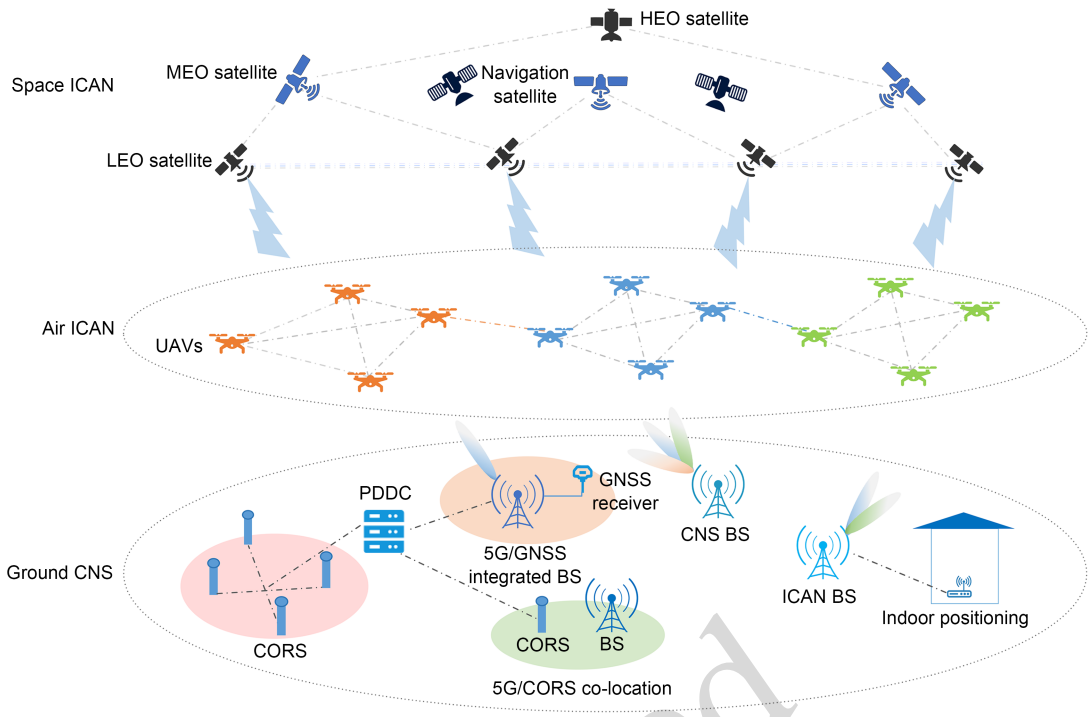

Fig. 7 Schematic diagram of low-altitude "space–air–ground" integrated and cooperative positioning scheme

Table 6 Components and functions of the low-altitude integrated and cooperative positioning

Communication/ Navigation technology	Functional description
GNSS	Provides fundamental positioning services.
GNSS + 5G	- 5G positioning compensates for GNSS denial environments. - Enables seamless indoor–outdoor integrated positioning. - Reduces the construction costs of CORS by leveraging 5G BS.
5G-A ISAC	- Provides terrestrial and low-altitude communication services. - Provides low-altitude sensing and surveillance services.
5G A2X	Enables ad hoc networking for UAV swarms.
5G SL	Enables cooperative positioning for UAV swarms.
BDS short-message	Provides communication services for high-altitude and remote areas.
LEO satellites	Provides positioning augmentation and communication services for high-altitude and remote areas.

(Section 5.4), this layer delivers communication and positioning services across the entire space domain.

In this scheme, the ground network supplies core high-precision positioning capabilities; the airborne network maintains cluster coordination when UAVs lose ground communication or GNSS; and the space-based layer extends coverage and provides redundancy for remote areas. The main advantages are as follows:

1. Cost reduction. A "communication-network-centric" integration reuses existing infrastructure, hardware, and spectrum, lowering LAIN construction and operational costs.

2. Information fusion. Breaking down data silos among communication, navigation, and surveillance enables multi-source fusion and collaborative benefits that enhance low-altitude flight safety.

3. Improved robustness. Three-dimensional coordination across space, air, and ground improves the robustness and reliability of UAV communication and positioning.

5.2 GNSS + 5G ground-based CNS

In the "space–air–ground" architecture, the ground CNS provides the primary positioning service for UAVs. It relies on integrated 5G and GNSS to deliver seamless indoor–outdoor high-precision positioning. Depending on the level of GNSS-5G integration, three practical ground solutions are summarized: (1) deploying CORS at 5G BS sites; (2) integrating GNSS raw-observation output into 5G BS hardware; (3) delivering positioning services solely via 5G.

(1) CORS co-located with 5G BS Sites

This approach uses existing 5G/5G-A sites to house CORS receivers and associated equipment, reusing site infrastructure such as power, backhaul, and data-center facilities. Broadcasting GNSS differential corrections to UAVs over a 5G communication link enables dynamic centimeter-level positioning. If BS supports ISAC technology, initial integration of communication, sensing, and GNSS positioning is possible. Co-location is a relatively low-coupling, low-complexity fusion strategy.

(2) GNSS-5G integrated communication–navigation hardware integration

In a deeper integration, the GNSS timing and receiver modules in a 5G/5G-A BS are upgraded to provide raw GNSS observations to a GNSS PDDC. The 5G BS then functions as an integrated node with both communication and high-precision navigation capabilities (Jin et al., 2025; Shi et al., 2025). Combined with 5G-A ISAC technology, this yields deep CNS integration at the hardware level on a single platform. As illustrated in Fig. 8, the architecture involves upgrading 5G BS by integrating GNSS RTK positioning into the BBU's timing module and adding radar-like sensing functionality to the AAU. Implementation complexity increases, but the long-term integration and operational efficiencies are higher.

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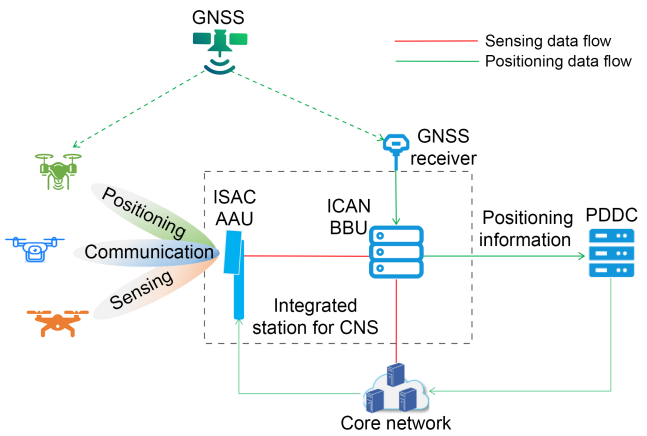

Fig. 8 Schematic diagram of integrated CNS based on 5G BS (Jin et al., 2025)

(3) 5G ICAN (5G-only positioning)

This solution explores the use of 5G/5G-A BS to provide positioning services without GNSS. Two principal methods are:

Co-band positioning, which introduces dedicated PRS that coexist with standard communication signals. Co-Band PRS enables continuous tracking of positioning signals with high ranging accuracy at low signal power (Yin et al., 2020; Deng et al., 2022). Downlink broadcast of PRS suits large-scale terminal deployment scenarios such as LAE and Internet of Vehicles.

In-band positioning, which derives location estimates from the characteristics of communication signals.

5G-A ISAC technology offers additional positioning via echo-based sensing; however, its positioning accuracy is currently limited compared with PRS-based approaches. Millimeter-wave and future 6G techniques promise further improvements in single-station accuracy (Yang J et al., 2021). The 5G-only approach is best suited for indoor or urban low-altitude applications; for broad outdoor UAV coverage, it must overcome the challenges of precise time synchronization between BSs and improved single-station positioning accuracy.

5.3 5G SL airborne ICAN

Reliable communication and precise positioning are essential for dense formation flying and cooperative UAV operations. In complex low-altitude environments, loss of communication or GNSS signals for some UAVs in a swarm can result in command loss, localization failure, formation disruption, and collision risk. To mitigate these risks, three complementary technologies support swarm resilience:

1. D2D communication, introduced in 3GPP Release 12 (3GPP, 2014), enables short-range direct links between terminals and allows disconnected UAVs to self-organize into a network.

2. A2X, specified in 3GPP Release 18 (3GPP, 2024b), supports aviation-specific communication among UAVs, air traffic control systems, and other aircraft.

3. SL, which uses SL PRS to provide high-precision inter-UAV ranging for real-time formation spacing and collision avoidance.

5G SL acts as an airborne supplement to ground GNSS + 5G ICAN solution, enabling precise cooperative positioning in low-altitude, short-range, and complex environments involving UAV swarms. As illustrated in Fig. 9, combining SL ranging with A2X/D2D communication creates a decentralized cluster subnet. UAVs continuously measure distances to neighbors using SL PRS and exchange real-time status information—position, velocity, heading—plus sensing data and collaborative control commands. If a UAV loses GNSS signals, its location can be computed from range and bearing measurements from three or more neighboring UAVs.

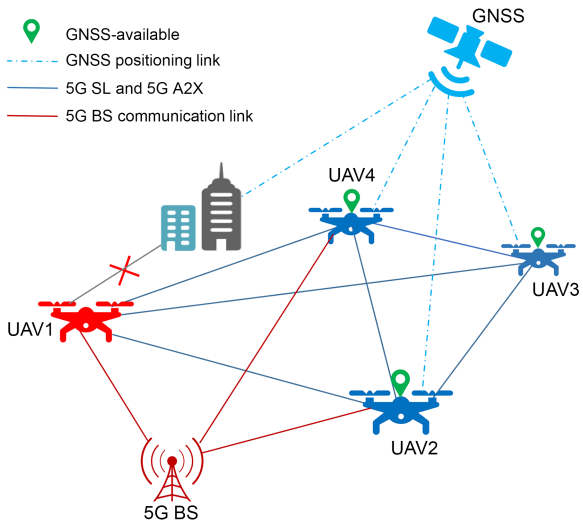

Fig. 9 Schematic diagram of collaborative UAV cluster positioning

This architecture enables UAVs to "perceive" their neighbors' positions and motion trends in real time; even if some units temporarily lose GNSS or ground links, the self-organized network preserves intra-swarm communication and localization, maintaining formation integrity and reducing collision risk. If the cluster lacks sufficient nodes for multilateration, the system falls back to GNSS + 5G or INS-aided estimation to retain spatial awareness.

5.4 GNSS + LEO satellite space-based ICAN

Space-based augmentation is critical for achieving seamless global coverage in the "space−air−ground" architecture. Deep integration of GNSS with LEO satellites and future 6G creates a space−ground communication−navigation network that provides wide-area, continuous, and resilient communication and positioning services, addressing coverage gaps over oceans, deserts, and mountainous regions. The LAE space-based ICAN framework centers on "GNSS + LEO satellite" augmentation and gains performance through multi-level fusion (Fig. 10).

LEO satellites, with lower altitude and higher received signal strength, can reduce multipath effects and provide stronger signals in urban canyons. They are well-suited for broadcasting differential corrections to UAVs or serving as additional ranging sources to augment GNSS positioning in challenged environments. Medium Earth orbit (MEO) satellites serve as the standard orbit for core GNSS constellations, providing baseline navigation. High-Earth-Orbit (HEO) systems and BDS short-message services provide a backup communication channel for remote operations, enabling UAVs to transmit positions and receive ground control commands when terrestrial networks are unavailable. The next generation of GNSS and inter-satellite links, combined with 6G-capable LEO constellations, will further improve global ICAN capabilities for UAV operations.

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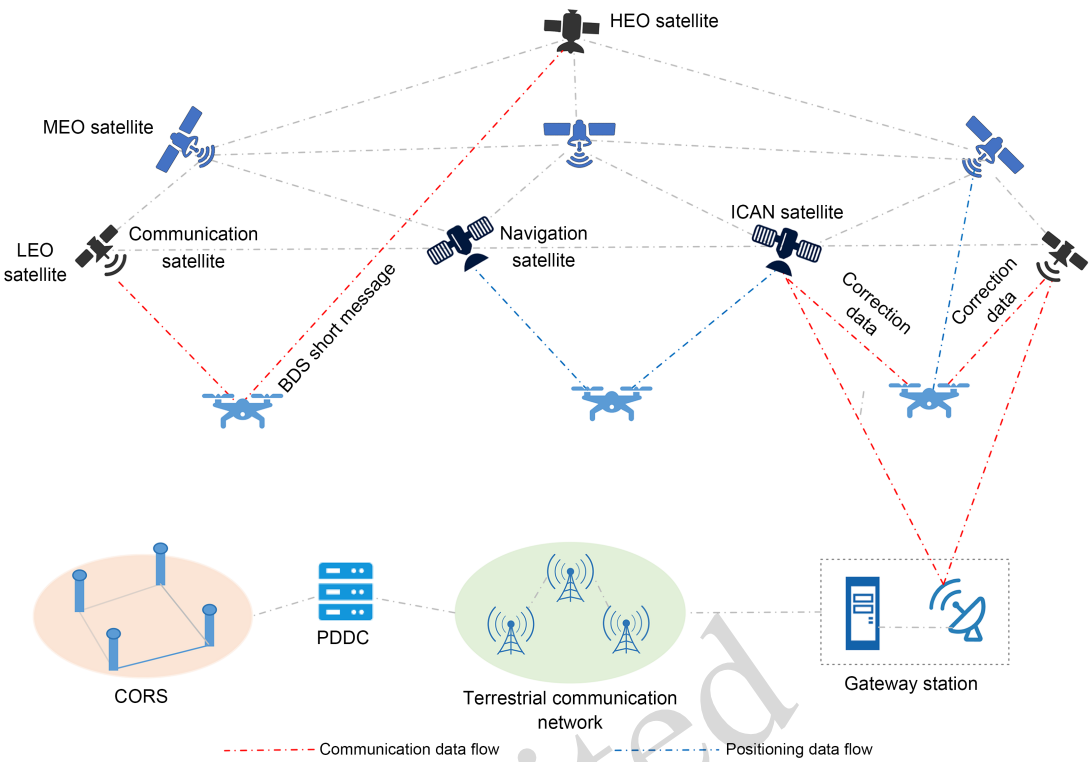

Fig. 10 Schematic diagram of space-based ICAN framework

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Space-based ICAN is not a standalone replacement but a complementary layer that, together with ground-based and airborne systems, forms a redundant "three-dimensional coordination" architecture. Ground-based 5G + GNSS provides primary high-precision positioning, airborne 5G SL clusters provide high-precision relative localization over short ranges, and space-based services supply global absolute calibration and backhaul resilience. The architecture is designed with terrestrial 5G networks as the primary. LEO communication satellites can directly assist UAVs beyond line of sight and link with ground stations to support backhaul and network synchronization, enabling centimeter-level positioning and global communication services even in remote and uninhabited regions.

6 Conclusions and prospect

6.1 Research conclusions

As a national strategic emerging industry, the safe and efficient development of LAE critically depends on high-precision, high-reliability, and wide-coverage positioning and navigation capabilities. This review addresses the urgent demand for advanced positioning technology in the LAE sector by systematically examining the navigation and positioning technology system within the LAIN environment. By evaluating the strengths and limitations of individual positioning technologies—GNSS, 5G, UWB, INS, visual localization, SLAM, and geomagnetic positioning—across accuracy, coverage, robustness, and cost, we show that multi-source heterogeneous fusion is the necessary approach for achieving high-precision, reliable positioning in low-altitude airspace. In particular, 5G positioning, as a wide-area, high-precision complement to GNSS, can help address continuity and accuracy issues for UAVs in challenging environments.

To address the high construction costs of LAIN, this review innovatively proposes a novel "space−air−ground" ICAN scheme built around existing communication infrastructure. This three-dimensional, hierarchical low-altitude positioning technology system leverages 5G deployments to enable deep reuse and integration of CNS functions, thereby effectively avoiding redundant network construction. Co-locating GNSS augmentation with 5G BS or integrating GNSS raw observations into 5G hardware reduces deployment and operational costs. Complementary airborne 5G SL collaborative networks and space-based LEO augmentation provide seamless indoor−outdoor positioning and extend short- to medium-range coverage, supporting integrated positioning and communication services for LAE.

6.2 Future outlook

Low-altitude positioning will evolve toward multi-source intelligent fusion, cluster-level collaborative positioning, communication−navigation−sensing integration, and space−air−ground coordination, enabling the large-scale development of LAE.

1. Multi-source intelligent fusion: Future work will concentrate on deep tight-coupling architectures and artificial intelligence-driven fusion. At the algorithmic level, research should move beyond traditional loose coupling and develop tightly coupled factor-graph optimization models that integrate GNSS, 5G, quantum inertial sensing, LiDAR, UWB, and other modalities. Artificial intelligence—particularly deep learning and federated learning—can optimize fusion algorithms, autonomously process large heterogeneous sensor streams, and increase robustness and adaptivity.

2. Autonomous collaborative positioning: Research should overcome single-UAV limitations by improving cluster-level performance

through distributed information sharing. Emphasis will shift to decentralized architectures and consensus mechanisms that support real-time collaboration in complex environments. Leveraging geometric relations among UAVs and environmental features can mitigate occlusion and multipath effects, strengthening cluster stability and enabling more reliable cooperative operations.

3. Integrated communication−navigation−sensing: Hardware coupling and network-level collaboration will reduce infrastructure cost and improve efficiency. Highly integrated 5G-A sensing BS combined with GNSS augmentation can deliver unified services—communication, positioning/navigation, and environmental sensing—on a single hardware platform. At the network level, intelligent hybrid network architectures should dynamically combine ground-based 5G, airborne A2X/D2D, and space-based BDS short-message and LEO satellite links to realize flexible, resilient, end-to-end coverage.

4. Integrated space−air−ground: With maturation of 6G, next-generation GNSS, and LEO constellations, coordinated "space−air−ground" CNS will be the long-term direction. Future networks will combine higher-accuracy terrestrial and satellite positioning, enhanced inter-satellite communications, and improved anti-interference measures to deliver comprehensive and reliable CNS services to low-altitude aircraft and support robust development of LAE.

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Author contributions

Yao JIN and Zhongliang DENG initialized the idea and designed the review framework. He ZHANG, Zhenke DING and Zelin WANG collected the literature for review and created all figures and tables. Yao JIN drafted the paper. He Zhang, and Zhenke DING helped organize the paper. Zhongliang DENG and Xiongyan TANG reviewed the paper and checked the writing details. All the authors revised and finalized 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.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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