

Spatial Situational Awareness for Safe UAVs in XAI-enhanced 6G Networks

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Abstract—Uncrewed aerial vehicles (UAVs) are disrupting both sixth generation (6G) mobile connectivity and urban air mobility (UAM), representing versatile and affordable aerial platforms. From 3D wireless and on-demand connectivity infrastructure to air taxis, spatial situational awareness represents a key component necessary to ensure safe UAV deployment, where collisions and accidents may not only cause network disruptions, but also non-negligible physical damages. Thanks to the real-time processing of high-resolution geospatial data, network coverage maps, and weather forecasts, UAVs can plan and adapt their missions dynamically. Given the necessity of empowering UAVs with intelligent learning-based algorithms, explainable artificial intelligence (XAI) enhances transparency and enables informed decision-making at all mission stages, ensuring trustworthiness of aerial operations. To this end, this work envisions XAI-driven spatial situational awareness as a foundational component for the safe integration of UAVs within UAM and 6G. It explores the integration of XAI into mission planning and real-time operations, ensuring reliable and safe operations even in challenging environments. The study introduces the concept, investigates key challenges, and provides insights into its potential across innovative use cases, including flying base stations, emergency response, and last-mile delivery.

Index Terms—6G, Explainable Artificial Intelligence (XAI), Uncrewed Aerial Vehicle (UAV), Urban Air Mobility (UAM), Spatial Situational Awareness

I. INTRODUCTION

Sixth generation (6G) infrastructure is leading the convergence of human-centric services related to communications, computing, control, localization, and sensing by bridging cyber and physical worlds through the improvement of data rate, reliability, and latency of past network generations [1], [2]. Given the major goal of achieving ubiquitous and pervasive connectivity, uncrewed aerial vehicles (UAVs), commonly known as drones, are unlocking low-altitude access to the air space for value-added 6G and urban air mobility (UAM) [3] use cases, ranging from last-mile delivery to timely on-spot coverage as flying base stations (FBSs) and air taxis.

Consequently, safety is of utmost importance, as these aerial entities have to face complex problems (e.g., dynamic physical occlusions, heterogeneous network coverage, and changing weather conditions) in intricate scenarios (e.g., smart cities,

irregular topographies, and challenging maritime areas), which hinder mission success [4]–[6].

Consequently, UAV awareness, i.e., the ability to perceive and interpret the surrounding environment, becomes a cyber-physical problem. Indeed, UAV decision-making models must rely on information that spans across different domains, including the environment digital twins, real-time occlusion perception, interference conditions, and short-term forecasts [5], [7]. Even though preliminary planning and simulations give confidence in the success of a mission, they are threatened by unknown obstacles blocking the path, sudden lack of network coverage, rain, or unexpected wind gusts [4], [6].

Given the diversity and non-linear relationships of mission-related domains, learning methods such as deep learning (DL), reinforcement learning (RL), and hybrid variants, support decision-making models for detecting and mitigating hazardous situations [4], [5], [8], [9]. However, the opacity of these methods limits their adoption, as operators and forensic analysts cannot understand how inputs drive inference decisions, reducing trust [10]. To overcome such limitations, explainable artificial intelligence (XAI) is emerging as a key component to provide safe models, which help to understand the system reasoning, determining the causation between the inputs and the outcomes [10].

To this end, the contribution of this work is to envision spatial situational awareness, hereafter referred to as SSA, as a critical yet under-explored problem in communications research for the safe integration of UAVs into 6G mobile infrastructure and UAM. The paper provides a background overview (Section II), identifies open challenges, and proposes a conceptual framework (Section III). Finally, Sections IV and V outline main use cases and key directions, respectively, to address them through XAI-driven decision-making, showing the potential of explainability to improve UAV safety, mission reliability, and social acceptance.

II. BACKGROUND

A selection of recent literature [1]–[3], [6], [7], [10], [11] focused on (A) 6G role in supporting UAM, (B) UAV challenges in physical environments, and (C) XAI adoption highlights the need of spatial situational awareness (SSA) for UAVs in 6G

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TABLE I
COMPARISON WITH MAIN RELATED WORKS.

Reference	Primary Focus	A	B	C
[1]	Role of UAVs in 6G	✓	✗	✓
[2]	6G open challenges and goals	✓	✗	✗
[3]	Review on current UAM challenges	✓	✗	✗
[7]	AI impact in UAV communications	✓	✓	✗
[10]	Potential of XAI in 6G use cases	✗	✗	✓
[11]	XAI-enhanced resource management	✗	✗	✓
[12]	UAV safety in UAM scenarios	✗	✓	✗
[13]	DL/DRL-assisted UAV safety for UAM	✗	✓	✗
This work	XAI-enhanced SSA in 6G UAM	✓	✓	✓

Topic legend: (A) 6G for UAM; (B) UAV potential; (C) XAI integration.

UAM. Still, there is a gap in addressing its specific challenges. Table I highlights how this work complements the existing studies, which are discussed hereby.

UAV safety in UAM scenarios was analyzed by [12], [13]. However, they are limited to the optimization of drone navigation solely through the risk assessment of population prediction, static obstacles, and collision avoidance with other aerial actors. Autonomous systems need transparent and interpretable decisions encompassing other essential factors critical for UAV safety, such as network coverage estimation for data rate and latency guarantees, forecasts, and most of all explanations. In this context, UAM represents a low-altitude mobility ecosystem where 6G capabilities, such as pervasive and ubiquitous connectivity, localization, sensing, and edge intelligence, support safe and reliable transport services [1]–[3], [7].

The highly mobile and heterogeneous components of UAM introduce substantial complexity in both network and transport management and coordination. Several open challenges hinder the full deployment of these solutions: (i) the real-time and scalable UAM, (ii) the detection, tracking, and identification of rogue and unauthorized drones that cause disruptions and collateral damage, (iii) the optimization of vertiports placements to ease last-mile and transport modality exchange, and (iv) social acceptance. SSA, i.e., the ability of UAVs to be aware of its surroundings and adapt its planning operations, remains critical and transversal across all these challenges [3].

In this regard, 6G improves reliable and low-latency connectivity to ensure guarantees on immediate data sharing and feedback on UAVs. By treating these platforms as part of a flexible network infrastructure, network digital twins ensure that both resources and traffic management are optimized to decrease the probability of mission failures [1], [2], [11].

AI is a key enabler of automation and optimization in 6G networks, where it is expected to become a native component across the whole architecture [1], [10], [11]. As illustrated in Fig. 1, AI supports intelligent sensing, e.g., weather monitoring, signal probing, and 3D environmental scanning, as well as data mining (for data fusion, historical analysis, and forecasting), control, and smart applications by enabling real-time data collection, feature extraction, resource management, and decision recommendations.

However, the adoption of AI, especially DL and DRL, in

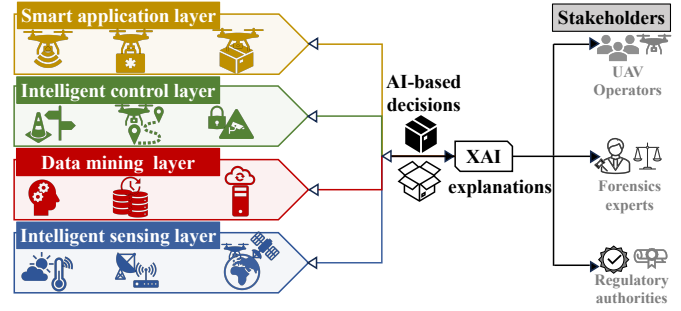


Fig. 1. AI/XAI-powered 6G architecture for safe UAV SSA. Multi-domain sensing data are processed to support trajectory adaptation, collision avoidance, and network-aware positioning, while XAI provides interpretable explanations and feedback-driven adaptation for reliable and privacy-aware decisions.

mobile networks is limited by the opacity of learning models. Their decisions often rely on complex parameters and non-linear transformations that are difficult for humans to interpret. This lack of transparency raises concerns related to robustness, feasibility, privacy, and trust, particularly when AI decisions affect safety-critical operations [10], [11].

XAI addresses these limitations by providing outcome explanations, thus improving trustworthiness in communication networks. In 6G, XAI can be integrated across the architectural layers to support different stakeholders: auditors assess privacy risks, operators diagnose erroneous decisions, and end-users receive understandable explanations for recommended actions. By offering descriptive, predictive, and prescriptive insights, XAI strengthens the transparency and accountability of AI-driven network operations [10].

Among the most common XAI techniques for 6G, model-agnostic methods such as SHapley Additive exPlanations (SHAP) and Local Interpretable Model-agnostic Explanations (LIME) are increasingly being adopted to explain model outputs without requiring access to the internal structure of the learning model [10]. These techniques can identify the most relevant features driving AI-based decisions and prioritize data samples or contextual information according to their inferred importance, thereby supporting more efficient and transparent decision-making.

Nevertheless, the role of XAI remains largely unexplored for safe UAVs, which operate in dynamic and complex environments. In this context, clarifying how AI models interpret environmental sensing, localization, and network data is crucial to enhance SSA. It supports adaptive trajectory planning, collision avoidance, and dynamic resource allocation, improving the safety, efficiency, and trustworthiness of both aerial communications and operations.

III. XAI-ENHANCED SSA

To lay the groundwork for XAI-enhanced SSA in 6G-enabled UAM, it is necessary to identify the key requirements and challenges.

UAVs are highly mobile platforms that require quality of service (QoS) guarantees in terms of latency, throughput, and

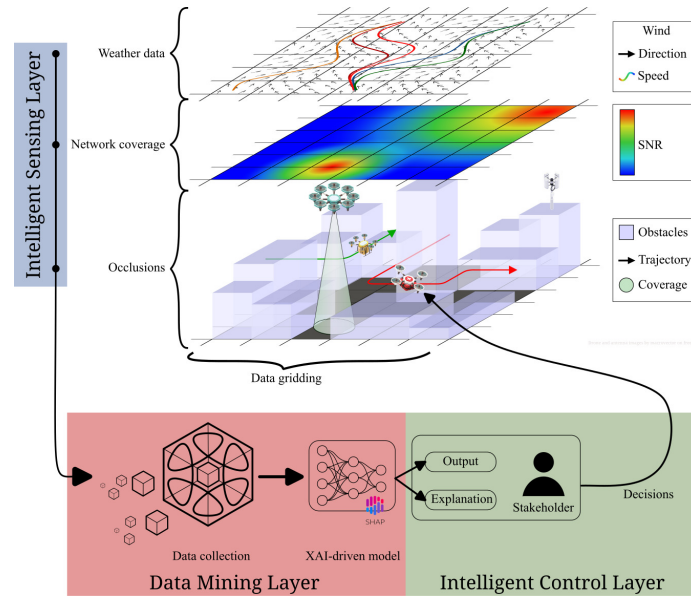


Fig. 2. Overview of key aspects for UAV SSA.

energy consumption to support reliable beyond visual line of sight (BVLoS) autonomous missions.

In this context, two main challenges arise. The first concerns the aggregation, storage, and timely processing of heterogeneous multi-modal data collected by both the UAV and the 6G network. These data include UAV energy consumption, weather conditions (e.g., wind turbulence, rain intensity, and electrical activity), network coverage, traffic conditions, and static and dynamic obstacles, all of which are critical for flight safety [4], [5], [13].

The second challenge concerns the design of XAI models able to provide explanations alongside predictions [14]. By processing the aforementioned data, these models support explained decisions, such as trajectory corrections, anticipated or postponed recharging, and other actions dependent on the specific use case.

Static risk frameworks were initially proposed to assess UAV flight conditions based on weather and network conditions [5]. However, 6G-enabled UAM scenarios require more adaptive approaches, where heterogeneous data sources are continuously collected, processed, and interpreted for mission planning and corrective actions.

Wireless coverage prediction models are broadly classified into model-based and data-driven approaches [9]. Model-based methods rely on statistical analysis, electromagnetic propagation models, or their combination. They typically exploit high-resolution digital terrain models (1m or below), georeferenced raster layers, and multi-class clutter maps to characterize the environment and evaluate low-altitude coverage [6]. Standard path-loss models account for free-space loss, diffraction, gas, and rain attenuation, while more accurate empirical, propagation-based, or ray-tracing techniques require dedicated simulators [9], [15]. Similar simulation tools can also support wind-turbulence analysis in urban areas

[5]. However, this processing often requires computational resources beyond typical UAV embedded systems, which are mainly optimized for sensing and lightweight AI inference. Data-driven methods, including random forests and DL-based models, estimate coverage indicators such as received signal strength by combining base station transmission power, 3rd Generation Partnership Project (3GPP)-based channel losses, and learned correction terms that compensate for discrepancies between empirical observations and analytical models [9], [13]. Recent studies have also investigated AI-based estimation of path-loss [16], [17] and cellular network usage [13].

Relative to the XAI-powered 6G architecture (Fig. 1), SSA affects the intelligent control layer, enhancing obstacle avoidance, path planning, network optimization, and safety principles. First XAI-based prediction models have been explored in related domains [15]. A light gradient boosting machine (LightGBM) model enhanced with SHAP was proposed for autonomous terrestrial networks, using calibrated ray-tracing data, 1m-resolution terrain and usage maps, and entity traces. During pre-processing, data gridding maps entity traces into coarser 10m spatial bins to reduce fast-fading variability and positioning errors, simplifying the dataset at the cost of potential model accuracy.

Accordingly, an XAI-enhanced SSA framework in 6G UAM is conceptualized in Fig. 2 by considering the following information:

- 1) *Weather* – Detailed current conditions and forecasts. Fine-grained processing of this information enables the model to be aware of the situation, its possible outcomes, and react quickly to address impending issues.
- 2) *Network coverage* – A detailed map of the radio access network and the perceived signal-to-interference-plus-noise ratio (SINR), to know the blind spots and detect overcrowded places. Furthermore, the map can

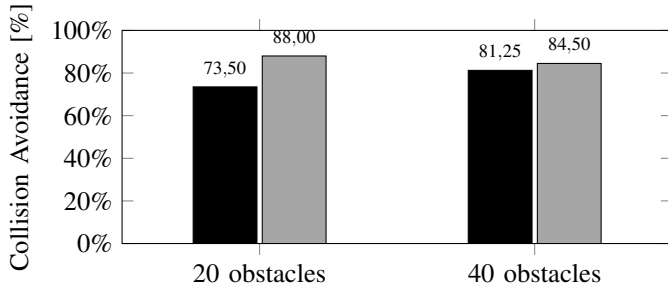


Fig. 3. Percentages of collision avoidance without (black) and with (gray) XAI in two scenarios.

be enhanced with historical QoS and the presence of supporting non-terrestrial networks (NTNs).

- 3) *Occlusions* – A reliable up-to-date digital twin of the surrounding environment, to know the obstacles, the orography, and relevant points of interest with geospatial attributes.

The data illustrated in Fig. 2 has been fixed to a certain altitude for the sake of simplicity. By sensing these aspects, the data is collected, processed (i.e., *data gridding* and *data mining*) to define a proper representation, and then fed to an XAI-driven model, which would provide inferences as *output* and *explanations* to *stakeholders*. These would in turn drive the decision-making process by establishing corrective actions to the UAVs in the form of *decisions*.

A preliminary investigation exploring such process and relying on a single synthetic data source examines the advantages of using XAI techniques discussed above over conventional AI approaches [18]. The study considers a simple scenario with one UAV and {20, 40} obstacles for trajectory optimization with collision avoidance [19]. In this context, interpretable RL based on Monte Carlo Tree Search can further support transparent sequential decision-making by explicitly exploring alternative actions and their expected outcomes before selecting the next maneuver. The percentage of collision avoidance is shown in Fig. 3. Even in this simplified setting, the preliminary results show that XAI improves collision avoidance performance, with gains of 14.50% and 3.25% for the scenarios with 20 and 40 obstacles, respectively, compared with the non-explainable case.

IV. COMPELLING USE CASES AND OPPORTUNITIES

SSA unlocks safe drones for 6G-enabled UAM. Moreover, by leveraging XAI, UAVs address their trust issues, as well as enhance their efficiency, safety, and reliability. Table II summarizes specific challenges and opportunities of this topic with respect to the given background on its role in 6G-enabled UAM, UAV SSA, and XAI integration. The most directly associated use cases are also highlighted for each challenge and opportunity and are discussed hereby.

A. Flying Base Stations (FBSs)

Mobile on-demand and on-spot coverage is a key 6G use case, where UAVs act as FBSs, i.e., temporary aerial access

points to extend, restore, or offload connectivity in areas with limited terrestrial infrastructure, such as disaster zones, rural regions, crowded events, and dense urban environments. While FBSs present major opportunities for seamless 3D connectivity and flexible coverage, their deployment is challenged by dynamic urban propagation blockages (e.g., severe non-line-of-sight conditions) and stringent size, weight, and power (SWAP) constraints. Consequently, their deployment requires more than coverage optimization, as FBSs must continuously adapt their position and radio configuration according to demand, backhaul availability, energy constraints, weather conditions, and airspace restrictions [20].

In this context, SSA supports safe and network-aware FBS operations by identifying 3D locations that maximize coverage under dynamic environmental conditions [7], as well as variations in SINR, latency, traffic load, and backhaul quality, while accounting for energy consumption and recharging [20]. This awareness is further empowered by integrated sensing and communication (ISAC), which introduces opportunities for unified hardware efficiency and sensing-assisted communication to facilitate proactive beam tracking. Nevertheless, adopting ISAC introduces new open issues, including security vulnerabilities due to broadcast signaling [21], [22].

XAI is crucial because FBS decisions are often produced by learning-based models that combine the discussed heterogeneous aspects [10]. Although XAI integration faces challenges such as high computational complexity on SWAP-constrained edge devices and the fundamental trade-off between model predictive accuracy and transparency, it improves network optimization, security awareness, and operational accountability. Instead of only recommending a new position or trajectory, an XAI-enhanced framework explains whether the decision is mainly driven by coverage improvement, collision avoidance, latency constraints, energy savings, or weather risk. For instance, a UAV may increase its altitude to improve coverage, move laterally to avoid blockage-induced low-SINR areas, or delay a maneuver due to predicted wind turbulence. These are key insights that directly benefit the stakeholders shown in Fig. 1 for UAV safety and accountability [20].

B. Emergency Response

In disaster-stricken areas where terrestrial infrastructure may be damaged or non-existent, UAVs establish seamless 3D connectivity to bridge aerial and terrestrial networks, offering flexible coverage [20]. This support allows first responders to coordinate rescue operations, exchange mission-critical data, and monitor affected areas. Through ISAC, UAVs rely on proactive beam tracking and communication-assisted sensing for BVLoS awareness, such as generating synthetic aperture radar images of the disaster zones. However, extracting precise sensing echoes in these scenarios remains hindered by severe clutter suppression issues caused by multipath [21], [22].

Beyond connectivity and monitoring, UAVs play a pivotal role in critical transportation during emergencies, delivering essential supplies to inaccessible areas [7], [20]. The combination of XAI techniques and SSA allows UAVs to adapt

TABLE II
SUMMARY OF 6G-ENABLED UAM RESEARCH DOMAINS, OPEN CHALLENGES AND OPPORTUNITIES FOR XAI-ENHANCED UAV SSA.

Domain	Challenges	Opportunities
6G-enabled UAM	● ■ Dynamic urban propagation and blockages	● + Seamless 3D connectivity and coverage
	● ■ Size, weight, and power (SWAP) constraints	● ■ Energy-efficient flight routes
	+ ■ Multi-UAV coordination and collision prevention	+ ■ Flexible and adaptive aerial service provisioning
UAV SSA	● ■ Trade-offs between sensing and communication	● ■ Integrated sensing and communication (ISAC)
	+ ■ Clutter in multipath-rich urban environments	● + Sensing-assisted communication
	● + ■ Low-altitude airspace safety and security	+ ■ Explainable risk-aware navigation
XAI integration	● ■ High computational complexity	● + ■ Interpretable network and mission decisions
	+ ■ Real-time interpretability constraints	● + ■ Transparent and explainable network optimization
	● ■ Trade-off between accuracy and transparency	● + ■ Informed decision-making

Use-case legend: ● = Flying Base Stations (FBSs); + = Emergency Response; ■ = Last-Mile Delivery.

to rapidly changing conditions, such as dynamic weather patterns, debris, or unstable terrain. XAI enhances the effectiveness and trustworthiness of UAVs in this high-stakes scenario [10], [22]: it provides opportunities for enhanced network transparency and security, allowing operators to understand AI evaluations and make informed decisions in complex, high-dimensional environments. During the planning phase, XAI enables operators to quickly analyze geospatial, weather, and network coverage data to design optimal flight paths. During flight, XAI-driven models provide insights into evolving conditions to ensure prompt course corrections. Nevertheless, its integration into highly dynamic networks introduces processing latency, complicating real-time operations where ultra-low latency is strictly required for autonomous flights [23].

Emergency response missions often occur in unstructured aerial traffic environments, where regulatory oversight may be minimal, but safety and efficiency remain paramount. XAI facilitates autonomous UAV navigation in these scenarios, ensuring compliance with overarching aviation safety standards [22]. Ultimately, whether restoring connectivity, monitoring disaster zones, or delivering critical supplies, the employment of UAVs in emergency response operations offers opportunities for innovative crisis impact mitigation strategies, provided that the physical layer trade-offs and computational constraints are jointly addressed [20], [23].

C. Last-Mile Delivery

Another relevant UAV use case in 6G-enabled UAM is the delivery of lightweight packages across dense urban areas, bypassing road congestion [7]. In this scenario, higher-frequency bands and ISAC capabilities can support high-capacity links, fine-grained localization, and real-time tracking. However, unlike generic aerial navigation, delivery missions require precise route planning up to constrained drop-off locations, facing challenges such as dynamic urban propagation with obstructions and collision avoidance in congested air spaces.

In this scenario, SSA must account for both mission-level and local delivery constraints. At the mission level, UAVs must balance travel time, battery consumption, network connectivity, weather exposure, and regulations. At the local level, they must adapt to short-range obstacles, wind gusts, reduced localization accuracy, and highly variable link quality during hovering, landing, and package release.

XAI supports SSA by fostering continuous and transparent network optimization, explaining why a delivery drone changes its planned route, delays a drop-off, selects an alternative landing area, or requests recharging before completing the mission [10]. For instance, an explanation may reveal the cause of a trajectory deviation, allowing operators to distinguish safety-driven decisions from inefficient behavior, supporting accountability in case of failed or aborted deliveries.

However, integrating XAI introduces substantial challenges, notably processing latency that threatens the ultra-low latency constraints required for real-time maneuvers, and the fundamental trade-off between predictive accuracy and transparency. Furthermore, delivery drones face stringent SWAP conditions, clashing with the high computational complexity of generating interpretable explanations. In this context, XAI can mitigate these demanding aspects by identifying the most relevant input features for decision-making, enabling model simplification, pruning, or edge-assisted execution without safety degradation.

V. CONCLUSION AND FUTURE DIRECTIONS

Spatial situational awareness for uncrewed aerial vehicles is a critical yet under-explored area in communications research, essential for the safe integration of drone-based 6G infrastructures and urban air mobility scenarios. This work offers a foundational overview and framework to contextualize this vision, highlighting open challenges and key recommendations for its realization. Additionally, compelling use cases are explored, demonstrating the potential of this research across various domains. At the core of this vision, the integration of explainable artificial intelligence (XAI) models with the 6G architecture is essential. These models must leverage accurate and reliable data from environmental obstacles, network coverage, and weather forecasts to ensure informed, transparent, and trustworthy decision-making. This framework lays the groundwork for future development, including reference XAI models, accompanied by appropriate evaluation metrics and robust network simulators, which enable effective network planning, forecasting, and adaptive operations.

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