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Introduction

1.1 UAV Applications

UAVs, known for their agility, rapid deployment capabilities, and autonomous operational characteristics, have increasingly emerged as critical assets across various civilian and military applications. In recent years, UAV technologies have demonstrated substantial advantages across numerous fields, driven by advancements in navigation systems, control algorithms, and hardware capabilities.

In environmental monitoring, UAVs are extensively deployed for real-time data collection, facilitating continuous surveillance and precise measurements of ecological parameters in regions otherwise difficult or hazardous to access [88]. UAVs equipped with advanced sensors and imaging technologies contribute significantly to biodiversity conservation, atmospheric pollution monitoring, and agricultural assessments, thereby enabling informed decision-making and rapid responses to environmental changes.

Disaster management scenarios have particularly benefited from UAV integration, leveraging their capability to perform swift and comprehensive aerial reconnaissance immediately following natural disasters, such as earthquakes, floods, and hurricanes [91]. UAVs provide critical situational awareness to rescue teams, allowing them to identify survivors, assess damage to infrastructure, and plan efficient emergency response strategies, significantly enhancing the effectiveness of rescue and relief efforts.

In the logistics and delivery sector, UAV technologies have revolutionized transportation and distribution systems, especially in remote or underdeveloped areas lacking reliable road infrastructure [164, 165]. UAV-based delivery services ensure

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the timely and efficient transport of critical supplies, such as medical goods, emergency equipment, and commercial products. This capability not only increases service accessibility but also reduces delivery costs and operational risks associated with traditional logistics methods.

Military applications have been profoundly transformed by UAV technologies, offering unprecedented capabilities for aerial combat, reconnaissance, surveillance, and strategic monitoring [96]. UAVs are extensively utilized for border surveillance, intelligence gathering, and combat support missions due to their stealth capabilities, endurance, and minimal risk to personnel. Autonomous UAV systems equipped with AI further enhance mission adaptability, allowing real-time decision-making and effective responses in dynamic combat situations.

Moreover, UAVs have found valuable applications in the fields of infrastructure inspection and maintenance, providing accurate, safe, and cost-effective alternatives to traditional methods. UAVs perform inspections of structures such as bridges, power lines, pipelines, and wind turbines, significantly reducing operational hazards and downtime. Additionally, in agriculture, UAVs facilitate precision farming by conducting detailed crop assessments, soil analysis, and targeted spraying of fertilizers and pesticides, greatly improving crop yield and resource efficiency.

These diverse and impactful applications have motivated extensive academic and industrial research aimed at enhancing UAV performance, operational reliability, and regulatory frameworks. As UAV technologies continue to evolve, it is expected that their integration into everyday life will expand, creating broader societal impacts and opening new horizons for innovation and technological advancement.

1.2 Sensing, Communication, and Computing of UAVs

The effectiveness and versatility of UAVs depend significantly on their capabilities in sensing, communication, and computing, which together determine the quality and scope of UAV-enabled applications. Recent advances in these areas have greatly enhanced UAVs’ functionality, enabling more sophisticated missions and improving operational efficiency.

In terms of sensing, UAVs are increasingly equipped with various advanced sensor payloads, such as high-resolution cameras, LiDAR, thermal imaging sensors, radar systems, and environmental monitoring instruments. These advanced sensing technologies enable UAVs to conduct highly precise and comprehensive environmental observations, infrastructure inspections, and target detections, even under adverse conditions. Furthermore, the integration of advanced sensing systems allows for real-time data acquisition and processing, supporting immediate decision-making processes during complex operational scenarios such as disaster management, precision agriculture, and surveillance operations.

Building on these sensing capabilities, context awareness has become a crucial aspect of intelligent UAV operation. It refers to the UAV's ability to perceive and interpret information about its environment, mission requirements, and network conditions in real time. By understanding factors such as terrain, weather, signal quality, and surrounding activity, UAVs can adapt their flight paths, sensing behaviors, and communication strategies accordingly. This enables more responsive and efficient operation, particularly in dynamic or uncertain environments such as disaster zones, congested airspace, or remote monitoring sites. Context awareness thus enhances the UAV's ability to make informed decisions and fulfill complex mission objectives effectively.

Communication capabilities are another critical component of UAV systems, playing a pivotal role in mission coordination, data transmission, and real-time control. Robust and reliable communication links between UAVs and ground stations (U2G), as well as among multiple UAVs (U2U), are essential to ensure continuous operation and timely data dissemination. Recent studies have emphasized the need to analyze and optimize UAV communication under challenging conditions, such as interference from ground-based transmitters and imperfect channel state information (CSI). Additionally, current research explores the communication capacity in three-dimensional (3D) environments, considering random UAV trajectories and dynamic network topologies, which significantly differ from traditional two-dimensional (2D) or static UAV deployments.

The computing capabilities onboard UAVs facilitate efficient data processing, autonomous navigation, and complex mission execution. As UAV missions become more sophisticated, onboard edge computing platforms have emerged as crucial components, enabling UAVs to perform data-intensive computations locally. This significantly reduces latency and bandwidth demands for data transmission. Edge computing capabilities are especially beneficial in time-critical applications, including disaster response, surveillance, and environmental monitoring, where immediate and accurate data analysis directly affects mission success. Moreover, advanced computing architectures allow UAVs to adapt dynamically to changing environments and make real-time decisions, enhancing the robustness and autonomy of UAV operations.

Collectively, advances in sensing, communication, and computing technologies significantly enhance UAV performance, enabling UAVs to operate effectively in complex and dynamic environments. Ongoing research continues to address remaining challenges and further improve these critical capabilities, thus broadening UAVs' applicability and operational effectiveness in diverse practical scenarios.

1.3 Mobility Models of UAVs

The mobility characteristics of UAVs play a critical role in determining the efficiency and effectiveness of aerial communication, networking, and sensing applications. UAVs are broadly categorized into fixed-wing and rotary-wing platforms, each governed by distinct aerodynamic principles and operational capabilities, which in turn shape their respective mobility models.

Fixed-wing UAVs are designed for high-speed, long-endurance missions, often used in wide-area surveillance and data collection tasks. However, they are subject to non-holonomic constraints, requiring continuous forward motion to maintain lift. As such, their mobility is often modeled using waypoint-based linear trajectories, where the UAV follows a sequence of predetermined points with fixed or adaptive speeds. Continuous, smooth trajectories that respect Newton's laws and the physical turning limitations of fixed-wing UAVs are constructed, offering flexibility for path optimization in cluttered environments.

In contrast, rotary-wing UAVs, such as quadcopters, possess vertical take-off and landing (VTOL) capabilities and are capable of hovering in place. This flexibility allows for precise maneuvering, making them well-suited for applications like infrastructure inspection, environmental monitoring, and delivery in urban environments. Their mobility is often captured using models, such as the random waypoint model, where UAVs select random destinations and move with randomized speeds and pauses, commonly used in simulation studies. More realistic models like the hover-and-fly pattern depict the typical stop-and-go nature of rotary-wing UAV missions, alternating between stationary observation and dynamic repositioning.

The choice of mobility model depends on the operational context and system design objectives. Accurate modeling is essential for analyzing communication link dynamics, evaluating network performance, and optimizing energy consumption in UAV-enabled systems.

1.4 UAVs Powered with AI

Recent advancements in AI have significantly expanded the operational capabilities and intelligence levels of UAV systems. By integrating AI-driven methods such as machine learning (ML), deep learning (DL), and reinforcement learning (RL), UAVs can autonomously address complex tasks with enhanced efficiency, adaptability, and robustness. This integration represents a transformative shift from conventional manually controlled or preprogrammed UAV operations toward more intelligent, autonomous, and adaptive missions.

One major application area of AI-aided UAVs is trajectory optimization and path planning. Utilizing RL algorithms, UAVs can autonomously identify optimal flight paths and adjust their routes dynamically in response to environmental changes, mission constraints, or unexpected events. Such adaptability is critical for missions in uncertain or hostile environments, enabling UAVs to maintain optimal communication links, avoid obstacles, and minimize energy consumption without continuous human intervention.

Moreover, AI techniques enhance the UAV's perception capabilities, significantly improving object detection, classification, and tracking accuracy. DL algorithms, particularly convolutional neural networks (CNNs), empower UAVs to interpret sensory data swiftly and precisely, which is indispensable for applications such as real-time surveillance, precision agriculture, infrastructure inspection, and disaster response. For instance, AI-powered UAVs are capable of autonomously detecting infrastructure defects or monitoring crop health, dramatically enhancing operational efficiency and reducing human oversight requirements.

AI-driven resource management and optimization further elevate UAV system performance. ML algorithms enable UAVs to effectively manage limited onboard resources, such as battery life and communication bandwidth. Predictive analytics allow UAVs to estimate energy consumption, anticipate potential system faults, and optimize resource allocation in real-time, ensuring mission sustainability and reliability. This ability is particularly important for prolonged missions requiring efficient energy use and high reliability.

In addition, AI plays a crucial role in enabling UAV swarms, a cutting-edge paradigm in UAV technology. AI algorithms facilitate coordinated decision-making, collective behavior, and distributed sensing among U2U, thereby achieving complex mission objectives that individual UAVs cannot efficiently accomplish alone. Swarm intelligence methods enable UAV groups to perform sophisticated surveillance, reconnaissance, environmental monitoring, and communication relay tasks with enhanced resilience to individual UAV failures or external interference.

AI is also a core enabler of adaptive, real-time decision-making across the UAV networks in sensing, communication, and edge computing. In particular, in AI-aided sensing, UAVs can autonomously interpret raw data from onboard sensors (e.g., cameras, LiDAR, and radar) using computer vision and DL techniques. This empowers them to recognize patterns, detect anomalies, or infer high-level environmental context without relying solely on remote processing. Such intelligent perception is crucial for tasks like target tracking, infrastructure inspection, or smart agriculture.

In AI-driven communication, learning-based methods such as RL, deep Q-networks, and graph neural networks (GNNs) enable UAVs to optimize spectrum access, trajectory-aware beamforming, and interference management in real time. This dynamic adaptation is essential in multi-UAV and UAV-to-ground networks, where link quality and topology vary frequently. In AI-enabled computing, onboard or edge-deployed AI models support distributed inference, caching, and decision-making with minimal latency. Federated learning and online learning approaches further allow UAVs to collaboratively improve their intelligence while preserving data privacy.

Together, these AI-aided capabilities enable UAV networks to operate more autonomously, efficiently, and securely, transforming them into resilient platforms for intelligent sensing-communication-computing fusion. This architectural paradigm not only enhances system performance but also expands the feasibility of complex missions in dynamic, adversarial, or resource-constrained environments.

Finally, the integration of AI with emerging technologies, such as reconfigurable intelligent surfaces (RISs) and edge computing, further extends the capabilities of UAV systems. AI methods optimize RIS configurations and UAV positions to significantly enhance communication coverage, link reliability, and signal quality. Similarly, edge computing augmented with AI provides real-time onboard processing capabilities, reducing latency and improving responsiveness, essential for time-sensitive operations like disaster response and tactical military missions.

1.5 Book Contributions

This book provides a systematic and comprehensive integration of current methodologies and theories in sensing, communication, and computing for UAV systems, with a particular emphasis on the application of advanced AI techniques. Its key contributions are reflected in the following aspects:

First, the book offers an in-depth survey and critical evaluation of UAV communication and connectivity in 3D environments. Unlike traditional studies that rely on simplified 2D or deterministic UAV deployment models, this work thoroughly addresses the complexities of 3D networks, including random UAV trajectories, network densification, interference management, and uncertainties in CSI. This structured review establishes a solid theoretical foundation for advancing the field.

Second, it systematically investigates existing methodologies in UAV trajectory optimization, energy efficiency, and beamforming strategies. By comparing various optimization techniques, the book highlights their respective advantages, limitations, and suitability for different operational scenarios. These insights are intended to assist both researchers and practitioners in selecting the most appropriate approaches for specific mission requirements.

Third, the role of AI in enhancing UAV intelligence is explored through a detailed review of state-of-the-art approaches in AI-driven trajectory planning, resource allocation, and autonomous decision-making. Techniques such as RL and DL are examined for their effectiveness in improving UAV autonomy, adaptability, and resource utilization.

Fourth, the book provides a thorough examination of UAV-enabled edge computing, including task offloading, scheduling strategies, and adaptive communication protocols. These discussions underscore the critical role of edge computing in enabling timely and efficient decision-making for time-sensitive UAV missions.

Fifth, emerging technologies, such as RISs, are also addressed. The book reviews AI-based optimization methods for integrating RISs into UAV communication systems, evaluating their ability to improve performance and reliability in dynamic and interference-prone environments.

Finally, the book includes extensive simulation results and performance evaluations derived from the existing literature. These empirical findings are critically analyzed to assess the practicality, efficiency, and limitations of the reviewed methodologies in real-world deployments.

By synthesizing and analyzing a broad spectrum of current research, this book serves as a reference for scholars, engineers, and industry professionals working with UAV systems. It consolidates existing knowledge and outlines promising research directions to guide future developments in this rapidly evolving field.

Several books have explored UAV communications, intelligence, and applications in recent years. Yet, they did not fully cover AI-empowered integrated sensing, communication, and computing for UAV networks, as done in this book. For instance, [197] focuses on the architecture, protocols, and performance aspects of UAV-based wireless networks, without addressing AI-driven optimization or sensing applications in depth. [206] offers a more recent look into computational intelligence methods applied to UAV communication, without considering sensing and in-depth AI computing. [135] covers theoretical modeling and practical UAV applications for different scenarios, without covering AI-driven architectures or communication-sensing-computing fusion. [11] focuses on urban applications of UAVs, without a generalizable or technical treatment of AI-enhanced UAV network design, or coverage of resilience, privacy, and real-time autonomy.

Unlike the aforementioned existing books, this book uniquely focuses on AI-enhanced architectures that tightly integrate sensing, communication, and edge computing within UAV networks. It emphasizes real-time autonomy, adaptive decision-making, context awareness, and resilience against security threats, supported by both theoretical modeling and AI-driven methods. This integrated approach is critical for the next generation of UAV systems operating in complex, adversarial, or resource-constrained environments, and fills a notable gap in current literature.

1.6 Book Outline

This book is structured to systematically review and analyze critical aspects of UAV technologies in the domains of sensing, communication, computing, and AI integration. In particular, each chapter is dedicated to a specific topic, ensuring comprehensive coverage of both theoretical foundations and practical implications.

Chapters 2 to 4 analyze the utility and integrity of UAV networks, and the threat of adversarial UAVs to terrestrial networks. Chapter 2 delves into the communication capacity and connectivity of UAV networks within complex 3D operational environments. It provides an in-depth analysis of U2U and U2G links, emphasizing challenges posed by random UAV trajectories, interference management, and network densification effects.

Chapter 3 investigates the vulnerability of terrestrial wireless communications to aerial eavesdropping from an information-theoretic perspective. The chapter presents a rigorous analysis of the ergodic secrecy rate and the average ϵ-outage secrecy rate for a ground-based transmitter-receiver pair intercepted by an aerial eavesdropper flying a random 3D trajectory with smooth turns within a spherical region.

In Chapter 4, the security risk is studied with cooperative UAV adversaries. This chapter focuses on the model that is extended to analyze the impact of coordinated eavesdropping strategies involving a swarm of UAVs using diversity techniques, such as selection combining (SC) and maximal ratio combining (MRC). The impact of oscillator phase noise and finite memory at the eavesdroppers is also incorporated. Closed-form approximations for ergodic and ϵ-outage secrecy capacities are shown to be asymptotically tight as the number of eavesdroppers grows.

Chapters 5 to 7 delineate the integration of AI techniques to UAV navigation and surveillance. Chapter 5 aims to address the problem of jointly optimizing UAV navigation and task offloading decisions in real time, under the constraint that the UAV lacks prior knowledge of IoT devices’ task queues, battery levels, and channel conditions. To tackle the uncertainty in network states, a GNN-assisted advantage actor-critic model is developed to capture the underlying relational structure among devices and guides the training of the UAV’s decision-making process.

Chapter 6 addresses the use of UAVs for radio frequency (RF) and video surveillance applications, emphasizing the integration of advanced communication technologies. It reviews approaches for trajectory optimization, power control, and stealth performance. This chapter illustrates how UAV systems have been optimized in previous research to balance performance and operational security effectively.

Chapter 7 discusses the emerging role of UAV-enabled legitimate monitoring systems via joint trajectory design and energy management. The system includes a suspicious transmission link with a terrestrial transmitter and a terrestrial receiver, and a UAV to monitor the suspicious link. Capitalizing on the successive convex approximation method, an efficient iterative approach is put forth to find a feasible solution fulfilling the Karush–Kuhn–Tucker (KKT) conditions. Numerical results demonstrate that with UAV trajectory optimization, the overall energy consumption can be greatly suppressed.

Chapters 8 and 9 describe the role of UAV and AI in emerging technologies (e.g., joint sensing and communications (JSAC) and RIS). In Chapter 8, a novel BS-UAV bistatic synthetic aperture radar (SAR) platform is designed, where the flight path of the UAV is optimized to minimize its propulsion energy and guarantee the required sensing resolutions on a series of landmarks. A new deep RL (DRL)-based online control scheme for visual-based UAV-on-UAV tracking and monitoring is proposed, where a solar-powered, fixed-wing UAV tracks a suspicious UAV target by having the target inside its effective visual range.

Chapter 9 presents a unified DRL framework for RIS-assisted UAV communications, addressing two critical scenarios: Covert radio surveillance and anti-jamming operations. By leveraging the latest twin delayed deep deterministic policy gradient (TD3) algorithm, a dual-mode intelligent control system is designed, which can dynamically optimize UAV trajectory and RIS configuration based solely on observed communication metrics, eliminating the need for explicit CSI.

Finally, Chapter 10 concludes the book by summarizing key findings, providing a synthesized view of current technological advances, and identifying open challenges and promising research directions in UAV sensing, communication, computing, and AI integration. This concluding chapter serves as a comprehensive guide for researchers and practitioners, highlighting critical insights and prospects for continued innovation in UAV technologies.

This book presents a unified exploration of integrated sensing and communication in UAV networks, supported by theoretical modeling and AI techniques. While not every chapter focuses explicitly on AI, the progression of the content builds a coherent path from fundamental modeling to AI-driven solutions. Chapters 2–4 provide foundational models for UAV communication and sensing—such as 3D mobility, link capacity, and interference management—under complex dynamics. These theoretical results are critical for designing scalable AI-driven strategies later in the book. Chapters 5, 8, and 9 explicitly implement AI techniques, including RL and deep neural networks, to optimize UAV trajectories, resource allocation, and collaborative behavior.

Chapters 6 and 7 focus on sensing and beamforming in challenging environments, offering insight into system-level constraints and opportunities for AI-based adaptation. Together, the chapters form a layered framework where fundamental analysis enables the deployment of intelligent decision-making in UAV-assisted networks. The book concludes with a discussion on limitations, real-world applicability, and directions for future research—particularly around security, online learning, and context-awareness.