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Future Integrated Network of Sensing, Computing, and Communication: Low-Altitude Economy under High-Speed Trajectory Tracking Dominated by General Artificial Intelligence

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Abstract. The rapid expansion of the low-altitude economy (LAE)demands highly reliable Unmanned Aerial Vehicle (UAV) systems. However, traditional UAV control engineering suffers from severe time latency inherent in its serial architecture and is significantly amplified in complex urban environments. To address this challenge, 6G-enabled Integrated Sensing, Communication, and Computing (ISCC) architectures are being utilised to reduce transmission delays. Furthermore, Large Language Models (LLMs) are introduced to shift the design paradigm of control engineering, aiming to improve decision timeliness through predictive state estimation and reasoning. This article reviews the advantages of coupling 6G ISCC with LLMs. The synthesis indicates that this integration effectively minimises system latency by substituting iterative mathematical calculations with direct semantic prediction, its transition to real-world deployment faces severe engineering bottlenecks where the intrinsic "black-box" hallucinations of LLMs are paramount. This paper concludes that autonomous UAV operations necessitate a fundamental shift toward Trustworthy and Explainable AI (XAI), coupled with high-fidelity digital twin validation, to guarantee system stability in safety-critical domains.

Keywords: Integrated Sensing, Communication, and Computing (ISCC), 6G, UAV tracking, Latency

1. Introduction

The Low Altitude Economy (LAE) is a comprehensive economic model operating within airspace below 1000 meters, utilizing aircraft as carriers to integrate and drive various regional industries [1]. Among the various types of aircraft used, UAVs are the most technologically mature and widely used aircraft in the LAE industry apart from helicopters.

However, the large-scale deployment of UAV fleets in urban canyon environments presents severe challenges on flight safety. These complex characteristics of urban causes significant physical obstructions and electromagnetic interference. This has reached the limit that traditional technological frameworks can handle [2]. To guarantee flight safety in such Global Navigation

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Satellite System (GNSS)-denied environments, systems demand new control techniques for higher control accuracy; this includes centimeter-level positioning and millisecond-level control responses. Ultimately, achieving this stringent precision relies on overcoming the critical bottleneck of time latency.

Therefore, this study focuses on the delay dilemma caused by the traditional separated four-layer control architecture: perception, communication, computation, and control. To overcome this structural dilemma, this paper focuses on the forefront, and examines the control paradigm evolution enabled by 6G-based Integrated Sensing, Communication, and Computing (ISCC) and artificial intelligence, exploring how these technologies collectively mitigate latency in modern UAV control systems.

2. The evolution of control engineering

2.1. Different challenges in dilemma

Modern UAV control engineering relies on a separate four-layer architecture: perception, communication, computation, and control (see Figure 1).

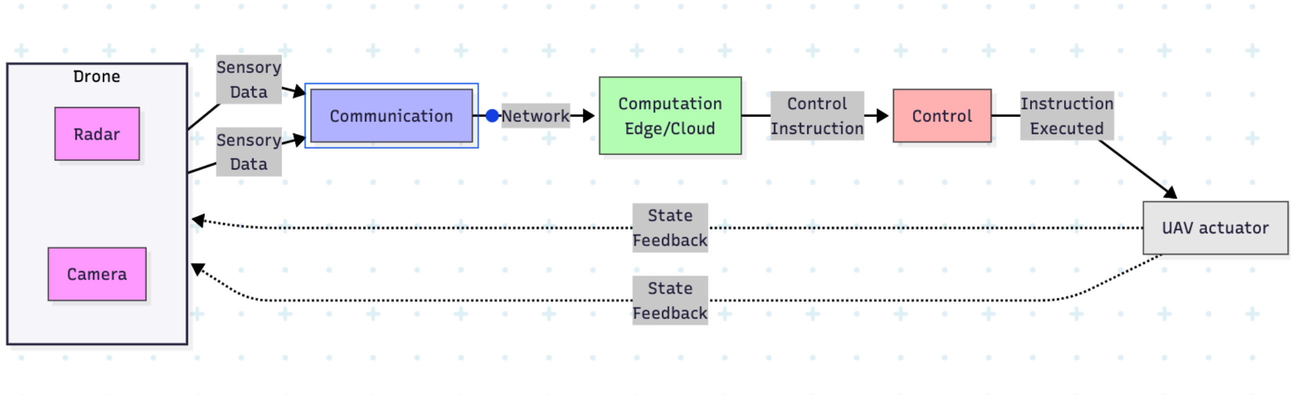

Figure 1. Four-layer architecture of modern UAV control

Within this framework, independent onboard sensors, such as radars and cameras, are responsible for environmental perception. The acquired data is subsequently transmitted to an edge or cloud computation platform via wireless networks. Following data processing, control instructions are generated and finally issued to the drone for execution.

Crucially, each link in this architecture introduces specific time delays, including perception acquisition latency, data transmission latency, and control command latency. The superposition of these delays severely degrades the real-time performance of the control system during high-speed maneuvering. Finally, the structural separation of communication and detection systems results in low spectrum resource utilization, creating additional bottlenecks [2].

2.2. Traditional optimization

Historically, Proportional-Integral-Derivative (PID) control was the most widely used traditional method for UAV tracking. However, PID relies inherently on delayed feedback loops, making its performance highly sensitive to sensing, communication, and computation latency. Furthermore, its inability to handle the non-linear dynamics of highly maneuverable flights fails to provide necessary tracking accuracy.

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To overcome these traditional bottlenecks, modern engineering has shifted focus toward advanced network architectures. In recent years, a considerable amount of research has been conducted internationally to prove that introducing Integrated Sensing and Communication (ISAC) based on 5G-advanced will improve spectrum and energy utilization efficiency [3].

Although 5G-advanced, which introduces innovations such as millimeter wave, has seemingly satisfying technical features such as higher bandwidth, it still forcefully adds sensing functions to the OFDM waveform of 5G's pure communication. The consequence of this forced addition is the severe and difficult to filter interference caused by high sidelobes [4]. Therefore, in order to clearly solve the problem of transmission delay, it is necessary to introduce 6G, which is expected to sense sensing fusion waveforms from the source. The ultra-reliable low-latency communication (URLLC) capabilities and high bandwidth of 6G provide the essential transmission backbone required for real-time UAV control.

Building upon 6G, end-to-end architectures like the Low-Altitude Digital-Intelligent Network (LADIN) have been developed to systematically optimize the four-layer control architecture and minimize latency at every stage [5]:

Bottom Layer (Data Acquisition): Orthogonal frequency-division multiplexing (OFDM) ISAC waveforms are applied to eliminate spectrum resource waste, thereby maximizing data acquisition efficiency.

Middle Layer (Data Fusion): A pluggable back projection adapter unifies multi-sensor data into a three-dimensional coordinate system, significantly reducing the processing latency typically caused by heterogeneous data integration.

Top Layer (Instruction Issuance): The Control and User Plane Separation (CUPS) principle decouples task data from control data. This prioritizes critical closed-loop control instructions, effectively minimizing transmission delays.

Despite these network-level improvements, computational delay during state estimation remains a critical challenge. To enhance delay robustness, modern control methods attempt to shift the paradigm from feedback to prediction. For instance, frameworks utilizing digital twins alongside an Extended Kalman Filter (EKF) and Proximal Policy Optimization (PPO) aim to estimate current states, allocate power efficiently and predict system evolution [6]. Similarly, Model Predictive Control (MPC) uses system dynamics models to calculate optimal control sequences in real-time [7].

2.3. The paradigm shift from ISAC to ISCC

While the aforementioned control optimization schemes, such as Model Predictive Control (MPC), offer improvements, they face significant limitations in highly dynamic environments. Primarily, MPC highly relies on strict mathematical models of drone dynamics. In complex urban canyons, the severe computational cost is necessary for keeping the accuracy of these models. Secondly, although the Integrated Sensing and Communication (ISAC) architecture partially mitigates feedback lag by accelerating data transmission, it remains fundamentally insufficien; the generation of the instructions is still based on past states and cannot achieve active prediction. Finally, in a standard ISAC framework, the perceived dimensions of the data are limited and must be transmitted to a central server for processing, which inevitably incurs terminal computation delays and potential information loss.

To resolve the persistent processing delays that ISAC cannot address, the Integrated Sensing, Communication, and Computing (ISCC) framework is introduced. ISCC fundamentally shifts the paradigm by embedding computational capabilities directly into the perception and communication

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nodes (edge computing). This deep coupling allows high-dimensional data—such as using Doppler shifts to determine radial velocity—to be processed on-site without being sent back to the central server [8]. Consequently, this localized computation drastically reduces terminal delays, enabling the control system to begin compensating for predicted deviations, marking the transition of the control system from reactive error feedback towards proactive advanced prediction.

2.4. Latency minimization: AI-driven state prediction

Building upon the localized computing foundation of the ISCC architecture, UAV control in high-speed scenarios must overcome the "too late when detected" dilemma. Traditional error feedback relies on compensating for past states, while mathematical prediction models demand time-consuming iterative solving. Therefore, the control engineering paradigm is shifting towards perception-driven state prediction, heavily empowered by Artificial Intelligence (AI) and Machine Learning (ML) [9].

The critical advantage of integrating AI within the ISCC framework lies in its ability to directly output solutions. Unlike traditional mathematical models that require complex, sequential equation solving, trained ML algorithms can instantly map current perceptual data to future micro-motion states. By bypassing the iterative calculation process, AI significantly compresses computational latency.

When the relevant data is sufficiently abundant and the prediction accuracy is robust, the system can be detached from the accumulated delay of the serial structure and the delay can be significantly compressed, achieving effective latency minimization. This synchronization between state prediction and instruction issuance is particularly crucial for multi-drone collaborative flights. In tight formations, replacing sequential, delayed commands with synchronized, AI-predicted state alignments significantly eliminates latency superposition, providing strong support for high-density and highly maneuverable drone operations.

3. The evolution towards large language models in ISCC

While traditional Machine Learning (ML) effectively predicts specific states, its task-specific nature struggles to adapt dynamically to the multi-objective complexities of urban canyons. Transitioning to Large Language Models (LLMs) offers a necessary paradigm shift. In the academic community, LLMs are not deployed as mere chat tools; rather, their massive parameter scale and contextual reasoning capabilities allow them to replace online optimization or handcrafted task-specific pipelines with offline pre-trained inference. This means a shift in artificial intelligence technology from "specialist" who undertake a single task to "generalists" who undertake a wide range of tasks. The multi-objective complexity that used to require multiple machine learning algorithms to handle is now only needed a single LLMs [10].

3.1. Accelerating decision-making via LLM

One promising application of LLMs is intelligent resource management within ISCC architectures, enabling rapid decision-making and efficient resource allocation. Traditional Multi-Objective Evolutionary Algorithms (MOEA) incur high computational complexity during spectrum and power allocation, translating to significant processing delays and difficulty in adapting to dynamic network environments. However, the introduction of LLMs transforms this dilemma. For instance, the LLM-enabled decomposition-based MOEA (LEDMA) utilises the LLM as a direct search operator guided

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by prompt engineering [11]. By solving multiple optimisation sub-problems simultaneously rather than sequentially, the LLM eliminates the optimization process in traditional MOEA, thereby significantly reducing the computational latency of the control system (see Figure 2).

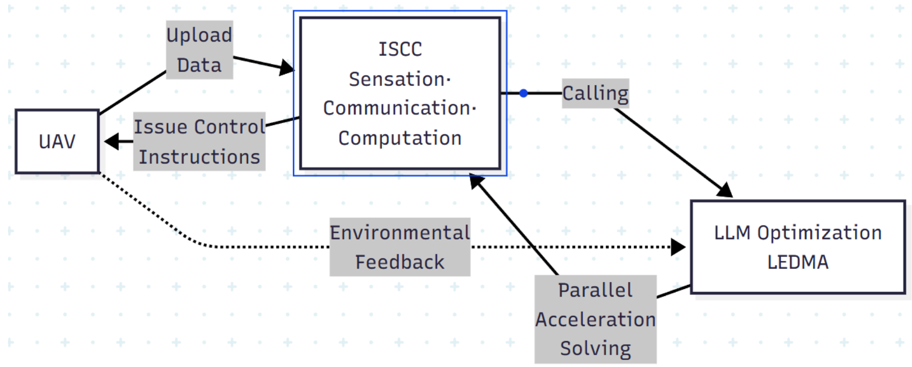

Figure 2. Interaction among LLM, ISCC and UAV for accelerated decision making

3.2. The ultimate challenge: the "black-box" dilemma

Despite their potential to minimize processing delays, the engineering implementation of LLMs in UAV control faces a critical, unresolved bottleneck: the "black-box" dilemma. Artificial Intelligence, especially LLMs, is often characterized as a black box that human completely incomprehensible on the meaning on its computation process. Unlike traditional mathematical control paradigms, which are fully interpretable, the decision-making processes of LLMs are generative and stochastic, hence LLMs exhibiting uniqueness model-intrinsic failure modes such as hallucination. In safety-critical domains like UAV operations, these vulnerabilities translate into an expanded cyber-physical attack surface, where errors can easily propagate into cascading operational or physical failures [12].

Currently, relying solely on the massive pre-training data of LLMs is insufficient to guarantee flight safety. Operators in critical infrastructure fundamentally require models that exhibit predictable, controllable, and explainable behavior—properties that general-purpose LLMs do not inherently guarantee. Unverified outputs from a black-box model lack the trust required for autonomous systems. Therefore, the cutting-edge challenge in utilizing LLMs for latency reduction does not solely lie in computational speed, but in developing Trustworthy and Explainable AI (XAI). Future research should necessitate rigorous standards for model transparency and verifiability, utilizing transparent and post hoc explanation models to ensure that the ultra-low-latency decisions made by LLMs are backed by safe and verifiable engineering standards [13].

4. Frontier challenges and future prospects

While the integration of ISCC and LLMs demonstrates outstanding potential in theoretical frameworks, transitioning these paradigms from ideal simulations to actual engineering deployments reveals several critical challenges. These practical engineering problems span from fundamental physical hardware limitations to algorithmic reliability.

4.1. Physical constraints from hardware

Current antenna technologies permit simultaneous signal transmission and reception on the same frequency band. However, transmission power typically exceeds reception power by over 100 dB, inevitably causing severe self-interference. Although self-interference cancellation (SIC)

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technologies have advanced, achieving the required minimum 55 dB attenuation strictly within the analog domain remains exceptionally difficult for compact UAV hardware [14]. Furthermore, physical circuit constraints—such as passive intermodulation (PIM) interference generated by printed circuit boards (PCBs) and thermal noise from onboard operational amplifiers—severely degrade signal integrity. This stray radiation complicates the isolation of received and transmitted signals, which may increase processing complexity and degrade real-time performance.

4.2. The paradox of LLM lightweight deployment

The deployment of LLM-empowered ISCC architectures encounters a formidable "Computing Power Wall." Conventional base stations operate under strict power budgets, rarely exceeding 2 kilowatts, rendering the deployment of full-scale LLMs—which consume hundreds of watts—unfeasible. To address this, lightweight architectures like the Mixture of Experts (MoE) model and techniques such as knowledge distillation and network pruning are utilized to customize base models. However, this introduces a severe "performance-accuracy" paradox. Lightweight designs inevitably compromise the semantic reasoning and generalization capabilities of the LLM. Although lightweight LLMs substantially reduce computational costs, inference latency on resource-constrained edge platforms may still exceed the timing requirements of latency-sensitive UAV control tasks. This is an entire order of magnitude higher than the strict ten-millisecond response time expected for highly dynamic UAV trajectory tracking.

4.3. Lack of system stability theory

In rigorous control engineering, having a mathematically proven algorithm is one of the most important factors when considering its practical application. However, the most unpredictable variable introduced by coupling ISCC with LLMs is the inherent "hallucination" of the neural network itself. Unlike traditional control algorithms evaluated through precise mathematical models and system stability metrics, the existing theoretical framework cannot define the upper bound of errors caused by LLM hallucinations. This absence of formal theoretical proofs and quantitative stability guarantees remains a fundamental obstacle preventing LLM-driven ISCC systems from transitioning from laboratory environments to large-scale, safety-critical commercial use.

4.4. The sim-to-real data dilemma

LLMs require massive volumes of high-quality, real-world data for effective pre-training and alignment. Nevertheless, collecting physical UAV trajectory data in complex urban canyons is prohibitively expensive and highly dangerous due to potential crash risks. Consequently, engineers heavily rely on digital twin simulations and mathematical modeling environments to generate training data. However, a significant "sim-to-real" gap exists; dynamic physical variables, complex aerodynamics, and unpredictable electromagnetic interference cannot be perfectly replicated in iterative simulation scripts. Training robust LLMs by leveraging simulation data, followed by adaptation or fine-tuning using limited real-world data to bridge the sim-to-real gap, remains a significant research challenge.

5. Conclusion

This paper systematically reviews the technological evolution of UAV trajectory tracking paradigms, specifically focusing on overcoming the critical bottleneck of time latency. The architectural trajectory has shifted from isolated perception and communication layers to a deeply coupled ISCC framework. Concurrently, the control logic has advanced from lagging error-feedback mechanisms to proactive, prediction-driven control. Ultimately, the introduction of Large Language Models (LLMs) pushes UAV control from "passive feedback" toward "active decision-making." While this decentralization of computational power possesses the potential to significantly mitigate the bottlenecks of traditional centralized UAV control, these theoretical achievements will remain confined to laboratory simulations unless the stringent engineering obstacles discussed in this paper are rigorously addressed.

As a critical review, this paper relies primarily on existing academic literature and theoretical deductions rather than empirical field data. Furthermore, because the deployment of LLMs in highly regulated physical systems is still in its infancy, the performance predictions regarding latency reduction contain a degree of theoretical foresight. The actual engineering costs—such as the strict power budgets, energy consumption, and complex thermal dissipation constraints on compact UAV platforms—require rigorous practical validation. Most importantly, the intrinsic "black-box" nature of LLMs necessitates further investigation into Trustworthy AI to ensure their ultra-low-latency decisions are safe and reliable. Therefore, aiming to bridge the "sim" to "real" gap could be one of the future hot points. Initial validation should focus on establishing high-fidelity digital twins and executing independent control system simulations using industry-standard environments like MATLAB and Simulink. Subsequently, physical UAV platforms should be deployed in controlled field tests to collect actual environmental and kinematic data. This empirical data will be indispensable for fine-tuning lightweight LLMs, verifying their stability bounds, and ultimately proving their real-world latency-reduction capabilities in highly dynamic urban canyon scenarios.

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