UNICO I+D Project
6G-SORUS-DRONE

SORUS-DRONE-A1.1-E2 (E5)

Final version of the architecture

Abstract

This deliverable presents an integrated architecture combining UAVs, virtualized RAN (vRAN), and Reconfigurable Intelligent Surfaces to enable adaptive B5G/6G networks. Through coordinated real-time and non-real-time control, UAVs operate as flying gNBs and RIS-assisted relays, dynamically extending coverage and optimizing network performance. Telemetry-driven optimization and seamless orchestration with vRAN and RIS demonstrate the potential of this approach for rapid deployment, capacity boosts, and resilient connectivity, establishing a foundation for intelligent, flexible future networks.

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List of acronyms

Unmanned Aerial Vehicle: UAV

Virtualized Radio Access Network: vRAN

Reconfigurable Intelligent Surface: RIS

Beyond 5G: B5G

Sixth Generation Networks: 6G

Real-Time: RT

Non-Real-Time: Non-RT

Radio Access Network: RAN

O-RAN Alliance (Open Radio Access Network): O-RAN

Central Unit: CU

Distributed Unit: DU

User Equipment: UE

Quality of Service: QoS

Radio Resource Control: RRC

Radio Link Control: RLC

Medium Access Control: MAC

Physical Layer: PHY

Global Navigation Satellite System: GNSS

Network Function Virtualization: NFV

Digital Twin: DT

Service Management and Orchestration: SMO

Radio Intelligent Controller: RIC

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Resumen Ejecutivo

Este entregable presenta una arquitectura unificada para la integración de Vehículos Aéreos no Tripulados (UAV) con Redes de Acceso de Radio virtualizadas (vRAN) y Superficies Inteligentes Reconfigurables (RIS) para crear infraestructuras de red inteligentes, adaptativas y resilientes más allá de 5G (B5G) y 6G. El trabajo introduce una arquitectura de control por capas donde los controladores en tiempo real (RT) gestionan la navegación de los UAV, las funciones de los nodos de radio y las configuraciones de las RIS, mientras que los controladores que no son en tiempo real (Non-RT) realizan la optimización predictiva, la planificación de misiones y la toma de decisiones basada en telemetría. Esta separación permite que los UAV actúen como gNB voladores o repetidores asistidos por RIS, reconfigurando dinámicamente la cobertura y la capacidad en función de las demandas de la red y las condiciones ambientales.

Demostramos cómo esta arquitectura apoya casos de uso críticos, incluyendo la restauración rápida de la cobertura durante cortes, aumentos temporales de la capacidad para eventos de alta demanda y la dirección de la señal asistida por RIS en entornos de propagación complejos. Al integrar la telemetría del vuelo de los UAV, las interfaces de radio y las operaciones de las RIS, el sistema permite la optimización basada en datos y facilita el uso de gemelos digitales para el modelado y la simulación predictivos.

Este enfoque se alinea estrechamente con los principios de las arquitecturas de red nativas de la nube y desagregadas en O-RAN, proporcionando una orquestación flexible a través de las capas aéreas y terrestres. El entregable también identifica y aborda desafíos clave como la coordinación de control de baja latencia, la gestión de interferencias entre los UAV y los nodos terrestres, y la comunicación segura en múltiples dominios.

Al unir la movilidad de los UAV, la programabilidad de las RIS y la virtualización de las vRAN, este trabajo sienta las bases para ecosistemas de red autónomos y auto-optimizadores capaces de adaptarse en tiempo real a la movilidad de los usuarios, las condiciones ambientales y las demandas del servicio. Sirve como un plan para desplegar infraestructuras aéreas y asistidas por RIS dentro de futuros sistemas B5G/6G, avanzando el estado del arte en el diseño de redes inalámbricas dinámicas e inteligentes.

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Executive Summary

This deliverable presents a unified framework for integrating Unmanned Aerial Vehicles (UAVs) with virtualized Radio Access Networks (vRAN) and Reconfigurable Intelligent Surfaces (RIS) to create intelligent, adaptive, and resilient beyond 5G (B5G) and 6G network infrastructures. The work introduces a layered control architecture where real-time (RT) controllers manage UAV navigation, radio node functions, and RIS configurations, while non-real-time (Non-RT) controllers perform predictive optimization, mission planning, and telemetry-driven decision-making. This separation enables UAVs to act as flying gNBs or RIS-assisted relays, dynamically reconfiguring coverage and capacity based on network demands and environmental conditions.

We demonstrate how this architecture supports critical use cases, including rapid coverage restoration during outages, temporary capacity boosts for high-demand events, and RIS-enabled signal steering in complex propagation environments. By integrating telemetry from UAV flight, radio interfaces, and RIS operations, the system enables data-driven optimization and facilitates the use of digital twins for predictive modeling and simulation.

This approach aligns closely with the principles of cloud-native and disaggregated network architectures in O-RAN, providing flexible orchestration across aerial and terrestrial layers. The deliverable also identifies and addresses key challenges such as low-latency control coordination, interference management between UAV and ground nodes, and secure multi-domain communication.

By bridging UAV mobility, RIS programmability, and vRAN virtualization, this work lays the foundation for autonomous, self-optimizing network ecosystems capable of adapting in real time to user mobility, environmental conditions, and service demands. It serves as a blueprint for deploying aerial and RIS-assisted infrastructure within future B5G/6G systems, advancing the state-of-the-art in dynamic, intelligent wireless network design.

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1. Introduction

The integration of Unmanned Aerial Vehicles (UAVs) into next-generation wireless networks is emerging as a transformative enabler for enhancing coverage, mobility, and responsiveness in dynamic environments. Recent advances in Virtualized Radio Access Networks (vRAN) and Reconfigurable Intelligent Surfaces (RIS) have introduced new architectural paradigms for programmability, control, and reconfigurability across the wireless stack, creating unprecedented opportunities for joint optimization with UAV platforms. This Deliverble presents a comprehensive analysis of the state of the art in architectural research that unifies these three technologies: UAVs, O-RAN, and RIS. Focusing exclusively on architectural and system-level scientific works, the report synthesizes how UAVs are being architecturally integrated as both clients and RAN elements within O-RAN, how RIS is being incorporated into programmable RAN control loops, and how the joint UAV–RIS control stack is evolving through RIC-driven design patterns, experimental testbeds, and standardization tracks.

1.1. vRAN Stack and integration with UAVs and RIS

As we explained in Previous deliverbales, In vRAN, the RAN is disaggregated into O-CU/O-DU/O-RU functions and exposed to software control via open interfaces (E2, A1, O1/O2). The Near-RT RIC hosts low-latency control xApps (≈10 ms–1 s loops) via E2, while the Non-RT RIC in the SMO hosts rApps (seconds-to-hours loops) and policies via A1; this is the control substrate most architectural works leverage for UAV and RIS integration [1, 2]. Recent tutorials and handbooks capture the RIC/xApp/rApp split, functional split 7.2x, and the development of E2 service models (E2SM-KPM/RC/CCC) as the architectural primitives for programmability [3].

1.2. vRAN and UAVs

For the integration between UAVs and vRAN, the most explicit architectural treatment is now formalized in ETSI TR 104 037 (April 2025), an O-RAN WG1 use-case analysis report that introduces two concrete UAV control/traffic architectures realized through RICs: (i) Flight-path-based dynamic UAV radio resource allocation, Non-RT RIC ingests UTM and environmental enrichment information, trains models/policies, and Near-RT RIC enforces per-UAV allocations over E2; and (ii) a UAV Control Vehicle architecture in which O-CU/O-DU, Near-RT RIC (and optionally Non-RT RIC) are edge-deployed in a mobile platform for low-altency control and high-rate uplink video, with A1/E2 loops mediating UAV-specific policies. These are complete O-RAN architectural stacks for UAVs, specifying data flows, function placement, and benefits of RIC-mediated closed-loop control [4].

Two complementary architectural lines are evident. First, UAVs as UEs with O-RAN policy control (as above). Second, UAVs as aerial RAN assets (flying RRHs/aerial BSs or relays) within cloudified RANs. Recent work on UAV-assisted C-RAN (UC-RAN) treats UAVs as flying RRHs attached to BBUs via

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fronthaul, outlining split and orchestration options and preliminary performance analyses, an architectural pathway compatible with O-RAN's split-7.2x and SMO/RIC control planes [5, 1].

Experimentation at scale: AERPAW and Open RAN air-mobility testbeds. The AERPAW program recently reported an O-RAN-enabled UAV experimentation architecture that integrates FlexRIC, key E2 telemetry (KPM), and xApps into an outdoor UAV testbed and its digital twin; this provides the first field-validated blueprint for plugging real UAV flight experiments into an O-RAN control stack and shows how O-RAN monitoring/optimization can be specialized for cellular-connected UAVs. Complementary work on Open RAN testbeds with controlled air mobility details design considerations for open, multi-vendor testbeds that can reproducibly exercise UAV mobility patterns under O-RAN slicing and RIC control, bridging lab and field. These testbeds give the community a replicable architectural environment for joint UAV–O-RAN studies. [6, 7]

In the evolving standards landscape for UAV connectivity, the architectural foundation is strongly influenced by 3GPP. O-RAN's UAV architectures build atop 3GPP's TS 23.256 (Release 17/18; most recent v18.4.0, April 2025), which defines architectural enhancements for UAS connectivity, identification, and tracking, including roles for UTM/USS and the 5GC interactions. Architectural works targeting UAVs in O-RAN consistently embrace TS 23.256's reference model for identification/authorization and telemetry flows, then layer RIC-mediated policies on top [8].

1.3. vRAN and UAVs

As Reconfigurable Intelligent Surfaces (RIS) move beyond purely physical-layer research, recent system-level contributions begin to integrate RIS into the O-RAN control plane, demonstrating how RIS control logic can be embedded into existing RIC/xApp frameworks. The "O-RIS-ing" and "RIS through RIC" prototypes define RIS optimization xApps within O-RAN, use FlexRIC/OSC Near-RT RIC, and implement closed loops in which a channel-monitoring xApp streams KPM over E2 and a RIS-optimization xApp (with policies from Non-RT RIC via A1) configures the surface. Both papers provide reference O-RAN testing architectures for RIS-enabled deployments and report multi-user performance measurements (e.g., configurable fairness vs. throughput), demonstrating feasibility but also exposing today's gaps (e.g., custom side-channels to drive RIS hardware and the lack of a standard RIS E2SM) [9, 10].

In parallel with these prototypes, RIS control plane proposals are increasingly being aligned with the O-RAN architecture through formalized system designs. Beyond prototypes, architectural proposals start to formalize a layered RIS control stack explicitly mapped to O-RAN. The TERRAMETA D2.2 (Sept 2024) deliverable defines a RIS Orchestrator (RISO), RIS Controller (RISC), and RIS Actuator (RISA), and maps their interfaces to O-RAN: RISO↔RISC via A1/O1-like interfaces; RISC↔RISA via a RIS Control Plane (RCP1) analogous to E2; and optional RISO↔RISA via RCP2 (O1/O2-like) for management. It also proposes new horizontal RIS–O-RAN interfaces (R1/R2) to enable joint optimization across RIC and RIS layers. This is the clearest system-level articulation of RIS control aligned with O-RAN to date [11].

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Finally, the broader specification landscape within O-RAN continues to evolve in ways that enable RIS integration. While there is no official E2SM for RIS yet, O-RAN's evolving E2SM set (e.g., KPM, RC, CCC) and E2AP updates provide the hooks to stream UE/cell measurements and to enact cell/beam controls that a RIS controller can subordinate or coordinate with. The O-RAN SC architecture overview and alliance blogs on new/updated specs document the present state of E2, A1, and O1 models that systems use to integrate RIS logic without modifying 3GPP interfaces [12, 13, 14].

1.4. UAVs and RIS

Where UAVs meet RIS: architectural roles and deployment patterns. The RIS–UAV literature has matured from algorithmic designs to system-level blueprints. Surveys and recent papers discuss three canonical architectures: (1) RIS-assisted UAV links (RIS on buildings to shape UAV–gNB/UE channels); (2) UAV-mounted RIS (U-RIS), where UAVs carry passive/active metasurfaces to create virtual LoS and improve coverage/localization; and (3) RIS at HAPS/NTN layers assisting UAV networks below. Recent works propose U-RIS for MEC, U-RIS for multi-target localization, and HAPS-RIS assisting UAV networks, each providing system diagrams and control/logical links (e.g., RIS control channels, trajectory-phase shift joint optimization). These are increasingly being framed in 6G NTN architectures with explicit RIS control links and function placement [15, 16, 17, 18].

1.5. Towards a Full Stack: integrating UAV, and vRAN, and RIS

Toward the full stack integrating UAV + O-RAN + RIS: A converged architecture is coalescing around the following pattern. (A) Non-RT RIC hosts AI/rApps that fuse external enrichment information (UTM flight plans, no-fly zones, weather), RAN KPM, and RIS telemetry to learn policies for UAV trajectories, beam/hand-off planning, and RIS configurations; policies are pushed via A1. (B) Near-RT RIC xApps run fast loops: UAV mobility and interference mitigation, traffic steering/slicing for UAV flows, and RIS phase/partition control, via gNB controls (RC/CCC) plus a vendor-specific RIS control plane; future stacks aim for standardized RIS E2SMs or RCP-like interfaces. (C) E2 nodes (O-DUs/O-RUs, possibly aerial O-RUs/F-RRHs) enact configuration; SMO manages inventory/O-Cloud and performance over O1; a RIS controller (RISC) interfaces either under the gNB (tight coupling) or parallel to it (loose coupling) [11]. (D) Edge placement: for mission-critical uplink (e.g., 4K video) a UAV Control Vehicle or edge site houses O-DU+Near-RT RIC and application servers; Non-RT RIC may stay central or follow to the edge. (E) For NTN/HAPS overlays, [19] recommends RIC-enabled handover/beam analytics and studies split/placement for transparent vs. regenerative payloads, directly applicable when UAVs operate under satellite/HAPS backbones with RIS assistance [20].

UAV and RIS add new control surfaces to the RIC. The literature highlights xApp conflicts (overlapping control on beams/scheduling vs. RIS phases) and ML brittleness/adversarial risks, a salient issue when UAV flight safety depends on RIC decisions. Conflict-mitigation frameworks (catalog-based detection/coordination at Near-RT RIC) and empirical studies of adversarial xApps are being proposed and validated; zero-trust and E2-interface hardening are parallel concerns. Such works are

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shaping architectural guidance for safe, multi-app deployments that will be crucial when RIS and UAV mobility controllers co-exist [21, 22, 23].

Instrumentation and service-model gaps. Prototypes reveal a gap in standard service models for RIS. State-of-the-art demos resort to custom side-channels (e.g., ZMQ/USB towards a RIS actuator) while using E2 KPM/RC for measurements and gNB control. Architectural proposals like RISO/RISC/RISA close this by defining interfaces aligned with A1/E2/O1 and by isolating fast “vertical” RIS control loops from slower orchestration, without breaking 3GPP/O-RAN contracts, setting the stage for future E2SM-RIS definitions [11].

Design guidelines distilled from the literature. (1) Close the loops at the right layer: keep trajectory control and RIS phase updates inside Near-RT RIC with tight telemetry (KPM) from aerial UEs/Nodes; leave flight-path planning, no-fly-zone policy, and long-horizon energy optimization to Non-RT RIC. (2) Treat RIS as a first-class RAN-adjacent entity: adopt a RISO/RISC/RISA stack with RCP-like links or press for an eventual E2SM-RIS to avoid brittle vendor APIs. (3) Exploit edge placement for UAV workloads: co-locate Near-RT RIC and O-DU with edge MEC to meet uplink latency/jitter budgets for control and video analytics (as shown by the Control-Vehicle architecture). (4) Plan splits for aerial nodes: when UAVs host O-RUs or F-RRHs, account for fronthaul variability; split-7.2x remains the pragmatic target with TSN support, but non-terrestrial contexts may require adaptive split and RIC placement as NTN papers suggest. (5) Engineer for safety and coexistence: adopt conflict-mitigation and zero-trust patterns in the RIC; verify xApps under adversarial scenarios before flight trials [4, 11, 24].

Open problems and near-term research directions. (1) Standardize RIS telemetry/control: define a RIS E2SM (or finalize RCP mappings) so RIS can be addressed as an O-RAN-managed resource with measurable KPIs, auditable policies, and conflict-aware control. (2) Joint xApp ecosystems: formal conflict detection/resolution across mobility (UAV), scheduling, and RIS xApps, with verified safety envelopes for flight operations. (3) Channel and synchronization at scale: airborne dynamics and RIS reconfiguration stress CSI pipelines; architectural works should specify where estimation runs (DU vs. RISC) and how its freshness is enforced through A1/E2/O1. (4) Split/placement for aerial O-RUs and NTN backbones: extend AERPAW-style stacks with adaptive splits and RIC placement for UAV/HAPS/LEO segments, reusing guidance emerging from O-RAN’s NTN studies. (5) Security and ZTA for RIC/RIS/UAV: adopt zero-trust and E2 hardening; ensure xApp provenance/run-time isolation; integrate UTM authentication and 3GPP TS 23.256 identification into RIC policy flows. (6) Energy co-design: especially for U-RIS, architectural stacks must expose energy states northbound and support Non-RT RIC optimizers (trajectory/EH scheduling), as emphasized in recent energy-centric surveys and U-RIS EH designs. [17, 25]

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2. General System Architecture

The integration of Unmanned Aerial Vehicles (UAVs) into next-generation wireless networks, particularly those aligned with Open Radio Access Network (O-RAN) and Reconfigurable Intelligent Surfaces (RIS), presents a transformative paradigm for enabling flexible, reconfigurable, and high-performance communication infrastructures. The architecture illustrated in Figure 1 embodies a layered and modular approach that ensures real-time responsiveness, spatial adaptability, and network-wide intelligence. This section elaborates on the design principles, components, and interactions of the architecture, emphasizing the real-time control loops and their roles in orchestrating UAV mobility, RIS coordination, and vRAN management.

At the top level, the architecture is structured around the **RT UAV controller**, which is able to communicate with the external **RT vRAN Controller** and **RT RIS Controller.** Additionally, the top level includes a **Non-RT UAV Controller**, which plays a key role in handling delayed or computationally intensive tasks not bound by strict latency constraints.

Both the RT UAV Controller and the Non-RT UAV Controller interface with a UAV platform consisting of subsystems for **navigation** and **network node control**.

The UAV is conceptualized as both a mobile infrastructure element (e.g., aerial base station, relay, or RIS host) and a computing node that can respond to network stimuli in real time. This dual function is enabled through the separation of control responsibilities across real-time and non-real-time domains, promoting both responsiveness and flexibility.

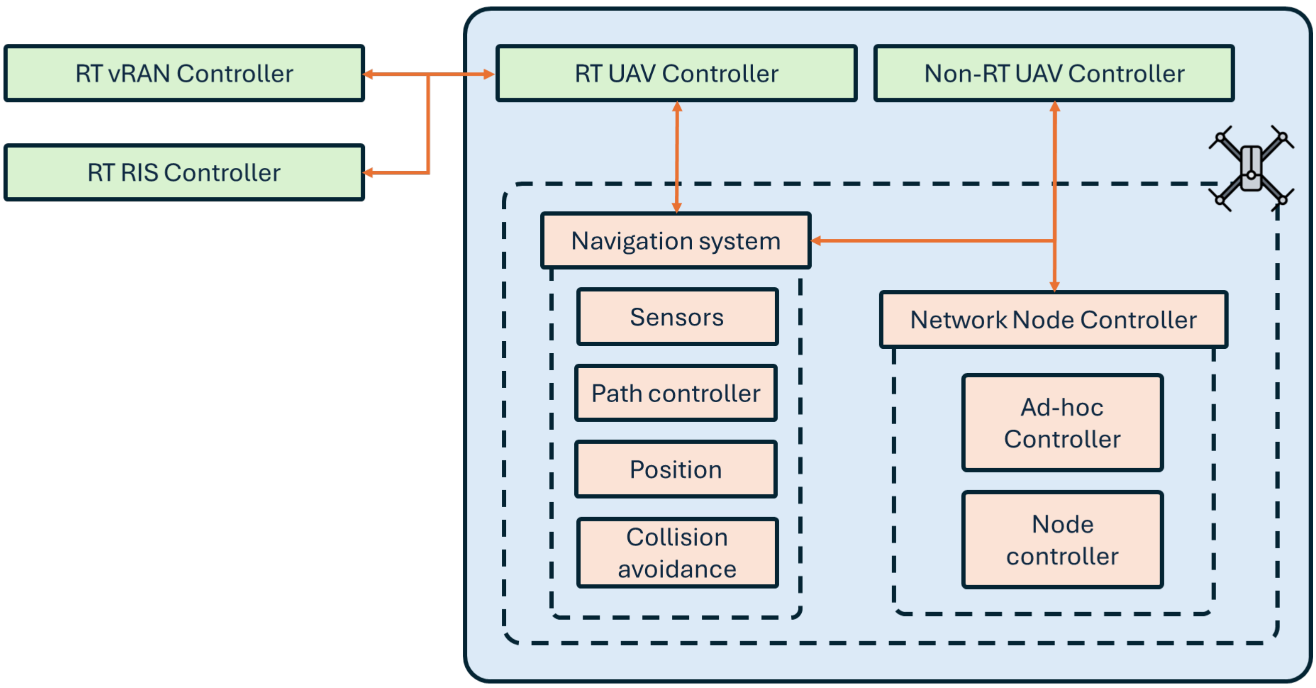

FIGURE 1 SPECIFIC UAV ARCHITECTURE WITH ITS CONTROLERS AND INTERFACES WITH RIS AND VRAN CONTROLERS

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2.1. RT UAV Controller and Navigation Subsystem

The Real-Time UAV Controller (RT UAV Controller) serves as the central decision-making component responsible for low-latency actuation and monitoring of the UAV's flight and positioning systems. It operates under strict timing constraints and interacts continuously with both physical and network-layer modules to ensure safe, efficient, and responsive UAV behavior. Its role becomes especially critical in scenarios where the UAV acts as a mobile infrastructure element—such as a flying base station or RIS platform—in a dynamic and often congested network environment.

The RT UAV Controller orchestrates the UAV's real-time navigation and mobility behavior, enabling it to:

- React to environmental changes such as obstacles, weather disturbances, and RF signal fluctuations
- Reposition rapidly in response to commands from the vRAN or RIS controllers
- Maintain continuous and safe flight through precise control of propulsion, heading, altitude, and velocity
- Support time-sensitive network tasks, including handover assistance, coverage adjustment, and RIS re-orientation

Its execution cycle is optimized for sub-second decision intervals, ensuring that flight dynamics and network demands are synchronized effectively.

2.1.1 System Architecture and Integration

As shown in the global system architecture, the RT UAV Controller sits at the intersection of multiple subsystems:

- **Navigation System** (downstream connection): It directly manages UAV movement via the Navigation System module, which comprises:
  - **Sensors** (IMU, GPS, cameras, LiDAR)
  - **Path Controller**
  - **Position Estimation**
  - **Collision Avoidance Engine**
- **RT vRAN Controller** (upstream connection): Receives movement requests, such as repositioning the UAV to optimize radio coverage, support UE density, or avoid inter-cell interference.
- **RT RIS Controller** (upstream connection): If the UAV carries a mounted RIS panel, this controller instructs the UAV to position itself to optimize signal reflection paths in cooperation with other RIS elements.

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- **Network Node Controller** (lateral connection): Ensures that the UAV's movement does not disrupt its role as a communication relay or access point, maintaining network continuity.

This tightly-coupled integration requires highly reliable and secure low-latency control links (wired, short-range wireless, or via an on-board bus) for stable closed-loop operations.

2.1.2 Core Functional Modules

Flight Stabilization and Path Execution: The RT UAV Controller provides real-time updates to the onboard flight computer based on the desired trajectory and environmental feedback. It computes:

- **Pitch/Roll/Yaw adjustments**
- **Waypoint tracking with velocity constraints**

It also continuously monitors deviations from the planned path and executes corrective actions to ensure spatial accuracy.

Collision Avoidance: Leveraging live sensor inputs (e.g., stereo vision, ultrasonic sensors, or LiDAR), the controller runs local obstacle detection and avoidance routines. Techniques include:

- Potential field-based repulsion from detected objects
- Emergency braking or rapid re-routing around transient obstructions
- Dynamic no-fly zone compliance

The system is designed to function autonomously but may defer to higher-level controllers if the response falls outside its authority or computation time budget.

UAV Positioning Feedback: The RT UAV Controller continuously updates position information using data fusion from GPS, IMU, and visual odometry. This feedback loop:

- Ensures accurate geolocation for vRAN and RIS alignment
- Aids the Network Node Controller in maintaining consistent beam steering or antenna pointing
- Helps in constructing real-time maps of the UAV fleet's spatial configuration for broader orchestration

Timing and Synchronization: All real-time computations are synchronized to a reference clock (e.g., GNSS-disciplined oscillator or IEEE 1588 PTP). This is vital for:

- Coordinated actuation across multiple UAVs
- Synchronization with radio transmission schedules
- Harmonization with RIS phase adjustments for coherent beamforming

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2.1.3 Real-Time Control Constraints and Design Considerations

The RT UAV Controller is subject to stringent constraints:

- **Latency budget**: Response time must remain under a defined threshold (e.g., 50–100 ms) for flight-critical operations.
- **Resource limits**: Computation is often limited to what can be executed on edge-grade processors or embedded SoCs onboard the UAV.
- **Isolation from non-RT tasks**: Non-RT tasks such as machine learning inference or large-scale planning are isolated to avoid jitter or delays in real-time execution.

Designing the RT UAV Controller often involves using real-time operating systems (RTOS) or safety-certified middleware (e.g., PX4, ROS 2 with real-time patches) to ensure task predictability and hard deadline guarantees.

2.1.4 Coordination with O-RAN Elements

The RT UAV Controller contributes to the O-RAN orchestration layer by acting as an **actuator node** that responds to control intents issued by the RAN Intelligent Controller (RIC) via the RT vRAN Controller. Use cases include:

- **Dynamic UAV repositioning to support traffic hotspots**
- **Coverage recovery during infrastructure failure**
- **On-the-fly creation of relay links or distributed MIMO topologies**

This interactivity requires adherence to open interfaces (e.g., E2, A1, and O1 in O-RAN), possibly translated into real-time commands for flight actuation.

2.1.5 Support for RIS-Enabled Use Cases

When the UAV acts as a RIS carrier, the RT UAV Controller must ensure:

- **Precise spatial alignment** with target UE and BS to achieve constructive interference
- **Micro-level adjustments** in hovering behavior to support static or dynamic beamforming objectives
- **Real-time compliance** with RIS Controller feedback to match phase alignment goals

This tight loop between UAV movement and signal behavior introduces additional complexity, necessitating a controller with highly accurate position estimation and fast response to RIS coordination commands.

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2.2. Network Node Controller and Ad-hoc Communication

On the communications side, the UAV embeds a **Network Node Controller**, which enables it to serve as an autonomous network function within an ad-hoc wireless environment.

2.2.1 Ad-hoc Controller

This module handles the configuration and maintenance of UAV-to-UAV or UAV-to-ground wireless links. Protocols such as OLSR or AODV may be used to support multi-hop routing, link estimation, and dynamic topology formation.

2.2.2 Node Controller

This submodule manages radio resources, handles UE association (when UAVs act as flying gNBs), and coordinates with the vRAN and RIS layers for dynamic network reconfiguration. It supports:

- Dynamic spectrum access
- Beamforming and antenna tuning (especially when integrated with RIS)
- Load balancing across aerial and terrestrial nodes

2.3. Non-RT UAV Controller

The Non-Real-Time UAV Controller represents the cognitive and planning layer of the UAV architecture, operating at relaxed latency constraints compared to its real-time counterpart. While the RT UAV Controller is tasked with immediate, safety-critical functions such as flight stabilization and obstacle avoidance, the Non-RT UAV Controller enables more complex, strategic operations that involve learning, optimization, and long-term decision-making. It bridges high-level orchestration intents—originating from central controllers, AI models, or digital twins—with the physical execution layer managed by the RT UAV Controller.

This separation of concerns enhances modularity, safety, and scalability, allowing UAVs to perform sophisticated roles in the network infrastructure without compromising real-time guarantees.

2.3.1 Functional Role

The Non-RT UAV Controller supervises several key functions:

- Long-horizon **trajectory planning** and reconfiguration
- **Mission coordination** across fleets of UAVs
- Integration with **machine learning models** for predictive decision-making
- Processing and summarization of sensor data for higher-layer controllers
- Support for **intent-based networking** (IBN) through abstraction and translation of goals

Operating in concert with O-RAN's Service Management and Orchestration (SMO) layer and RICs, the Non-RT controller executes decisions based on network metrics, environmental data, and user demand forecasts.

Architectural Integration

The Non-RT UAV Controller interacts with several architectural elements:

- **RT UAV Controller**: Provides trajectory updates, mission goals, and performance policies to be translated into actuation commands.
- **RT vRAN and RIS Controllers**: Receives feedback about network conditions (e.g., throughput, interference maps) and translates this into UAV positioning strategies or RIS coverage plans.
- **Navigation and Network Node Systems**: Passes higher-level configurations, such as preferred operational zones, energy-aware routing paths, or temporary no-fly regions.

This controller may be physically located on the UAV (e.g., as an embedded AI processor), on an edge node (e.g., MEC server), or in the cloud, depending on mission constraints and available connectivity. This placement flexibility allows for computational offloading and energy conservation.

Key Functional Components

- **1. Trajectory and Coverage Planning**

One of the primary responsibilities of the Non-RT UAV Controller is to plan UAV movement and positioning with a broader temporal and spatial context than what real-time control permits. This includes:

- Computing **energy-optimal** paths given battery constraints and coverage objectives
- Optimizing **hovering points** for acting as base stations, RIS relays, or sensing agents
- Generating trajectories that avoid congested airspace or adhere to UAV flight corridors
- Coordinating with neighboring UAVs to achieve **fleet-level coverage and redundancy**

Advanced techniques such as A*, RRT*, or deep reinforcement learning can be employed here, taking advantage of the relaxed timing constraints to explore large solution spaces.

- **2. Learning-Based Adaptation**

The Non-RT controller acts as the integration point for learning-based modules, which may include:

- **Mobility prediction** of users or base stations to proactively reposition UAVs
- **Radio map construction** using collected signal measurements and crowd-sourced data
- **Fault detection and isolation** by analyzing telemetry for signs of drift, calibration error, or component wear
- **Autonomous mission reconfiguration** in case of changing objectives or unexpected failures

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Such algorithms typically require significant compute resources and storage, reinforcing the utility of offboard Non-RT controllers in edge/cloud environments.

- **3. Energy Management and Charging Optimization**

Battery life is a critical constraint in UAV-based systems. The Non-RT UAV Controller:

- Estimates energy consumption for planned trajectories
- Recommends mission schedules that respect battery limits
- Schedules **charging operations**, either by routing to known charging stations or by coordinating with UAV swarms for **in-flight role switching**

It may also factor in **payload weight**, temperature, and wind conditions to dynamically adapt energy budgets.

- **4. Digital Twin Integration**

In advanced deployments, the Non-RT UAV Controller interacts with a **digital twin**—a virtual replica of the UAV and network environment. This allows:

- Pre-mission simulation and validation
- What-if analysis for coverage or network load impacts
- Testing of new control policies before field deployment

The digital twin may include models of physical dynamics, RF propagation, energy consumption, and user mobility.

- **5. Semantic Interface to Orchestration**

Unlike the RT controller, which responds to explicit and low-level commands, the Non-RT UAV Controller interfaces with the orchestration layer using abstract **intents** or policies. For example:

- "Maintain 95% coverage over Zone A between 12:00–14:00"
- "Reduce interference in Subband X by repositioning aerial RIS elements"
- "Maximize throughput for high-priority UEs in Sector B"

It interprets these intents and derives action plans or UAV formations accordingly.

Multi-UAV Coordination

In multi-UAV environments, the Non-RT Controller facilitates:

- **Fleet planning and partitioning**, assigning roles and areas to each UAV
- **Collision avoidance at the mission level**, avoiding congested regions through long-term planning
- **Formation flying** for joint communication objectives (e.g., distributed MIMO, coordinated RIS reflection)

- **Data sharing and synchronization**, enabling cooperative SLAM or RF mapping

This requires consensus algorithms or distributed optimization techniques, and in some cases, a centralized fleet management agent.

Collaboration with O-RAN and RIS Controllers

The Non-RT UAV Controller plays a key role in aligning UAV operations with the O-RAN architecture:

- It communicates with the **non-RT RIC** to receive high-level service goals, optimization strategies, or network analytics.
- It coordinates with the **RT RIS Controller** to determine feasible UAV positions for optimal RIS panel deployment.
- It informs the **RT UAV Controller** about long-term repositioning requests and constraint boundaries (e.g., altitude limits, exclusion zones).

By handling these tasks out of band, it allows RT control loops to operate with minimal interference, improving both performance and safety.

Security, Reliability, and Resilience

The Non-RT UAV Controller must be robust against:

- **Cyber threats** such as spoofed mission commands, denial-of-service attacks, or ML model poisoning
- **Faults in the RT layer**, triggering fallback behaviors or recovery missions
- **Communication outages**, through support for delayed synchronization and autonomous fallback routines

To support these, the controller may include:

- **Redundant communication paths**
- **Authenticated intent channels**
- **Mission buffering** for temporary autonomy
- **Model validation and certification** frameworks

Deployment and Scalability Considerations

In practice, the Non-RT UAV Controller may be instantiated as:

- **Onboard AI modules** (e.g., NVIDIA Jetson or Intel Movidius devices)
- **Edge services** on MEC platforms within the RAN
- **Cloud-native microservices**, part of a network slice assigned to aerial operations

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Containerized implementations allow for rapid deployment, scalability, and lifecycle management through orchestration tools like Kubernetes, ensuring that mission planning and optimization functions can scale with UAV fleet size and network complexity.

2.3.2 Real-Time Controllers for vRAN and RIS

The **RT vRAN Controller** governs the disaggregated RAN functions, potentially split across centralized and distributed units (CU/DU). It dynamically allocates computing, spectrum, and transport resources based on the positions and capabilities of UAV-mounted or ground-based nodes. Its responsibilities include:

- Coordinated scheduling for UAV-based and terrestrial cells
- Fast handover management in response to UAV movement
- Instantiation and migration of VNFs (Virtual Network Functions)

The **RT RIS Controller** is responsible for configuring RIS panels, which may be ground-based or UAV-mounted. These panels are used to reflect or steer wireless signals to optimize coverage, minimize interference, and improve energy efficiency. The RIS Controller:

- Adapts RIS phase shifts and amplitudes in response to environmental changes
- Coordinates with the RT UAV Controller to reconfigure RIS orientation in mobile deployments
- Integrates with the vRAN Controller to fulfill higher-layer QoS and throughput objectives

RIS functionality benefits significantly from UAV mobility, as aerial RIS can dynamically reposition to serve areas of poor coverage or to establish NLoS bridges.

2.4. Inter-Controller Coordination and Workflow

All real-time controllers operate in tight coordination, sharing updates and triggering actions through secure and low-latency communication links. The architecture supports the following workflows:

- **RT vRAN ↔ RT UAV**: Updates UAV positions to optimize RAN topology dynamically.
- **RT RIS ↔ RT UAV**: Adjusts RIS parameters as UAVs reposition, ensuring optimal reflection angles and minimal latency.
- **RT UAV ↔ Navigation System**: Executes flight paths, adjusts for collisions, and maintains stable positions.
- **Non-RT UAV ↔ RT UAV & Network Node Controller**: Sends trajectory updates and strategic control inputs.

This coordination facilitates a **closed-loop orchestration system**, essential for use cases such as disaster recovery, temporary event coverage, and rural connectivity.

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3. Use Cases and Benefits

This integrated architecture enables multiple emerging 6G use cases:

- **UAV-Aided RIS Coverage Extension**: UAVs with mounted RIS panels can be deployed on demand to cover shadowed areas or to support beam steering in mmWave/THz bands. This is Further explored in Section 5.
- **On-Demand Aerial gNBs**: UAVs acting as full 5G base stations with vRAN integration, supporting traffic surges or coverage holes.
- **Dynamic Network Slicing**: Through the coordination of RT controllers, UAVs and RIS can participate in on-the-fly slice reconfiguration and isolation.
- **Digital Twin Synchronization**: The non-RT controller may interact with a digital twin platform for network prediction, anomaly detection, and planning.

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4. Challenges and Research Directions

Despite its potential, this architecture presents several challenges:

- **Latency Constraints**: Ensuring hard real-time responsiveness in RT control loops over wireless links is non-trivial.
- **Interference Management**: UAV-based nodes can introduce unpredictable interference unless tightly coordinated.
- **Security**: Securing communication and control signaling among all controllers, especially in ad-hoc and UAV-assisted scenarios, is essential.
- **RIS-UAV Co-optimization**: Developing joint optimization algorithms for RIS tuning and UAV trajectory remains an open problem.

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5. Creating B5G/6G network coverage maps for better management

The architecture of our UAV system has been refined to make it smarter and more adaptable for handling network coverage missions in B5G and beyond. It's now divided into two main parts: the UAV Orchestrator and the UAV Controller. These work together to manage network resources efficiently, make real-time decisions, and seamlessly integrate with modern networks.

UAV Orchestrator: Planning and Deployment

The UAV Orchestrator takes care of the big-picture planning. It defines where the UAV will operate (the area of action), sets mission parameters, and manages network slices—basically ensuring the UAV's mission fits within the broader network services.

One key feature of the orchestrator is that it uses Transformer-based models to predict network traffic. These models analyze time-based patterns and help forecast what network usage might look like in the next 10 minutes or so. With this information, the orchestrator can send the UAV to areas where network demand is expected to rise, ensuring coverage is always available where it's needed most. This predictive power is essential in environments where network usage fluctuates frequently.

The orchestrator also connects with different network layers through a cross-layer API management system, which helps it communicate with the infrastructure. This means it can adjust the mission in real-time, based on what's happening in the field.

UAV Controller: Real-Time Operations

While the orchestrator focuses on planning, the UAV Controller is where all the real-time action happens. It's designed to help the UAV adapt on the fly using several key modules:

- Behavior Optimization Module: This module works with base stations (BSs) to adjust the UAV's flight path based on live network data. By predicting where coverage is most needed, it ensures the UAV moves to the right areas to fill coverage gaps. This keeps the UAV's actions aligned with current network needs.
- RAN-Based Navigation and Coverage Mapping: The UAV uses Radio Access Network (RAN) data like RSSI and SNR to guide its movements. If an area has weak signal strength or high demand, the UAV adjusts its flight path to provide better coverage. This module also helps the UAV create an up-to-date coverage map, showing the network's performance across the area it's flying over.
- Collision Avoidance and Localization: To ensure the UAV navigates safely, we've integrated passive radar systems. These systems allow the UAV to detect obstacles without emitting any signals of its own, relying instead on existing infrastructure signals. This is especially useful in places where GPS might not work well, like in cities with tall buildings. The localization feature helps the UAV maintain precise positioning, even in complex environments.

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How the Orchestrator and Controller Work Together

The orchestrator and controller don't work in isolation—they are constantly in sync to keep the UAV mission on track and adapt to changing network needs. The **UAV Orchestrator** handles high-level decisions, like predicting where network demand is likely to increase based on historical data and real-time patterns, while the **UAV Controller** ensures that these predictions translate into efficient action in the field. This dynamic interaction ensures that the UAV is always at the right place at the right time, making the most of available resources to optimize coverage.

Imagine a scenario where a large outdoor event is taking place in a city park. As the event unfolds, the network traffic begins to surge, with thousands of people streaming video, sharing on social media, and accessing other data-heavy services. The orchestrator, monitoring this activity, predicts a spike in traffic in the area and identifies a potential coverage gap that could lead to poor service quality if not addressed quickly. In response, the orchestrator dispatches several UAVs to the park to enhance coverage in that specific region.

As the UAVs arrive at the scene, the **UAV Controller** in each drone kicks in, taking over from the orchestrator to ensure precise real-time adjustments. Using live data from **Radio Access Network (RAN)** metrics such as RSSI (signal strength) and SNR (signal-to-noise ratio), the UAVs constantly adjust their flight paths to ensure they're positioned in the most effective spots. Some UAVs might hover over areas where the signal is weak, providing immediate coverage relief, while others focus on gathering data for real-time **coverage mapping**, which is fed back into the system to further optimize performance.

In this scenario, the system operates collectively. UAVs communicate and coordinate with each other to avoid overlap and ensure full coverage. For example, if one UAV detects high signal strength in a certain zone, it will move to a different area where the signal is weaker, ensuring that every corner of the park receives sufficient coverage. This real-time adaptability prevents network overload and ensures that users at the event experience smooth and seamless connectivity.

Additionally, the orchestrator keeps track of network usage over time, ready to reassign the UAVs as the demand shifts. For instance, as the event progresses and people move to different parts of the park, the orchestrator might reallocate UAVs accordingly, ensuring that they are always positioned in areas with the highest demand. Throughout this process, the orchestrator and controller continuously share information, updating one another on network conditions and making adjustments as necessary.

This example highlights how the orchestrator and controller work together to ensure that UAVs are not just deployed strategically, but also operate in a way that maximizes their effectiveness in real-time. The UAVs don't simply follow a pre-set plan—they adjust dynamically, reacting to live conditions and ensuring optimal coverage and service quality even in the face of unpredictable or changing demands.

6. Summary and Conclusions

The deliverable presents a cohesive exploration of how UAVs can be integrated with virtualized RAN (vRAN) and Reconfigurable Intelligent Surfaces (RIS) to create a flexible and intelligent networking framework for beyond 5G and 6G scenarios. We began by establishing the foundational context of vRAN integration with UAVs and RIS, describing how disaggregated network functions can be dynamically extended to aerial platforms. This enabled UAVs to operate not merely as user endpoints or relays, but as active network elements capable of hosting RAN components, forming ad-hoc extensions of terrestrial infrastructure, and enhancing coverage in underserved or high-demand areas. We also explored how RIS technology complements this approach, using programmable surfaces mounted on UAVs or deployed on the ground to improve propagation, mitigate blockages, and steer signals dynamically to where they are most needed.

Building on this foundation, we moved toward a full-stack architecture that unifies UAV mobility, vRAN flexibility, and RIS reconfigurability within a single integrated system. This required harmonizing both real-time and non-real-time control loops, ensuring that flight control, radio resource management, and RIS configuration work in concert. We introduced a general system architecture that defines clear interfaces between controllers and subsystems, showing how RT controllers handle immediate, latency-sensitive operations (such as UAV positioning or RIS beam adjustments), while Non-RT controllers leverage predictive intelligence, telemetry, and planning tools to optimize performance over broader time horizons. This layered design allows UAVs to adapt quickly to network demands while remaining guided by higher-level policies.

The deliverable then delved into the RT UAV Controller and Navigation Subsystem, outlining how low-latency control supports safe and precise UAV operation, even in dynamic or congested environments. We examined its integration with navigation sensors, path controllers, and collision avoidance mechanisms, highlighting how real-time adjustments are essential for maintaining stable positions and supporting functions like beam alignment or RIS orientation. Complementing this, the Network Node Controller was introduced as the UAV's interface to the radio domain, enabling it to manage user associations, control radio resources, and coordinate spectrum usage across aerial and terrestrial layers. Through this integration, UAVs effectively transition into aerial gNBs or RIS-assisted relays, seamlessly extending the RAN's footprint.

We also described the Non-RT UAV Controller, which adds intelligence, prediction, and mission planning capabilities to UAV operations. This controller processes telemetry, predicts demand hotspots, optimizes UAV trajectories, and coordinates energy usage and fleet deployments. Its interaction with digital twin models enables offline simulation and validation, bridging the gap between operational control and long-term strategic planning. This is closely tied to the RT vRAN and RIS Controllers, which manage virtualized network functions and programmable surfaces in real time, while sharing data and commands with UAV systems to ensure cohesive orchestration.

The architecture was further contextualized with use cases demonstrating its potential: UAV-based coverage recovery during disasters, on-demand capacity boosting in event hotspots, RIS-enabled non-line-of-sight connectivity in dense urban areas, and the ability to generate high-resolution coverage maps for optimized network management. These scenarios underscored the benefits of combining UAV mobility, RIS reconfigurability, and vRAN virtualization into a single adaptive platform.

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