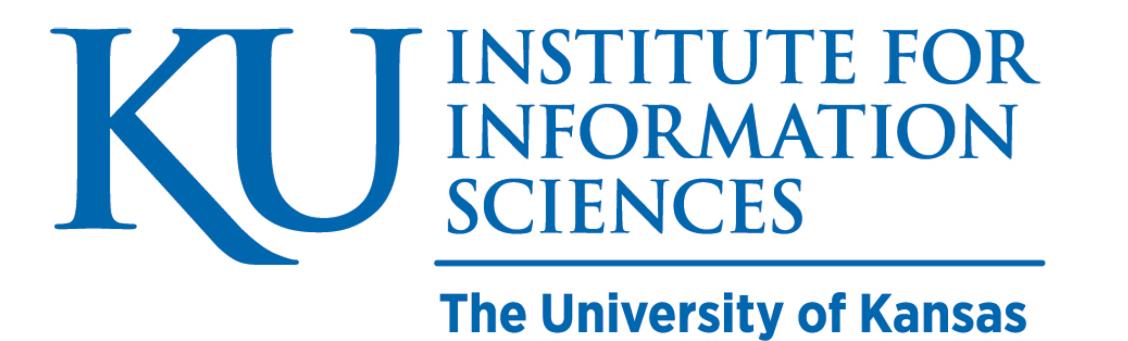


AeroSpec: An Adaptive Spectrum Framework for Autonomous Aerial Systems: Optimization, Decentralized Markets, and Deployment

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Introduction and Background

- To fully unlock the potential of unmanned aerial systems (UAS) and advanced air mobility (AAM) technologies, most flights will need to operate beyond visual line-of-sight (BVLOS).
- The control and non-payload communication (CNPC) link is critical for ensuring safety and demands an *interference-protected aviation-grade* spectrum.
- While there has been significant interest in the airborne use of flexible-use spectrum and existing mobile networks, there is no licensed spectrum in the U.S. for UAV communications, leading operators to rely on unlicensed or experimental licenses without protection from harmful interference.
- In January 2023, the FCC issued an NPRM on licensing UAS use of the 5030–5091 MHz band; in March 2024, NTIA's National Spectrum Strategy proposed repurposing it for commercial airborne use, and in January 2025 the FCC authorized terrestrial CNPC communications in part of the C-band for NNA services.

Overarching Goal of the Project

The overarching goal of this project is to develop adaptive spectrum management, sharing, and monitoring while ensuring interference protection for safety-critical CNPC communications in BVLOS. The proposed framework includes foundational and algorithmic solutions for *co-existence optimization*, *cooperative sensing*, and *decentralized market design*. The proposed solutions will be rigorously validated using *multiagent aircraft flight tests* leveraging 5030-5091 MHz radios.

Motivations

The existing spectrum management techniques across various frequency bands such as TV White Space, the CBRS (Citizens Broadband Radio Service) in 3.5 GHz, and the 6 GHz band with Automated Frequency Coordination (AFC) are not directly applicable to aerial use cases due to several reasons.

- Efficient sharing while ensuring interference protection. Adaptive spectrum management, sharing, and monitoring solutions are needed to ensure interference-protected and reliable CNPC link for *all* aerial operations, even those with *opportunistic* access.
- Need for more accurate spatiotemporal interference models. UAVs operate in three dimensions, which adds complexity to their channel modeling and height-dependent interferences. Furthermore, existing interference models, such as those in CBRS, are overly conservative, leading to reduced spectrum utilization.
- Lack of sensing frameworks for aerial systems' spectrum. In addition to authorized service parameters such as transmitted power profile and duty-cycles, it is necessary to know actual spectrum usage, either through measurements or improved data reporting. The CBRS environmental sensing capabilities (ESC) are not suitable for protecting incumbent and primary aeronautical licensees at 5030-5091 MHz.

Objectives

- Dynamic access has been widely studied, but for aerial systems the key objective is ensuring *interference-protected spectrum access*.
- To improve spectrum utilization, advanced reservation approaches that provide stable and reliable access become essential, given that reducing transmit power and transmission cessation mid-flight are not feasible.
- The growing use of machine learning (ML) for spectrum situational awareness, automated resource management, and real-time spectrum monitoring and enforcement is a promising approach.

Intellectual Merit

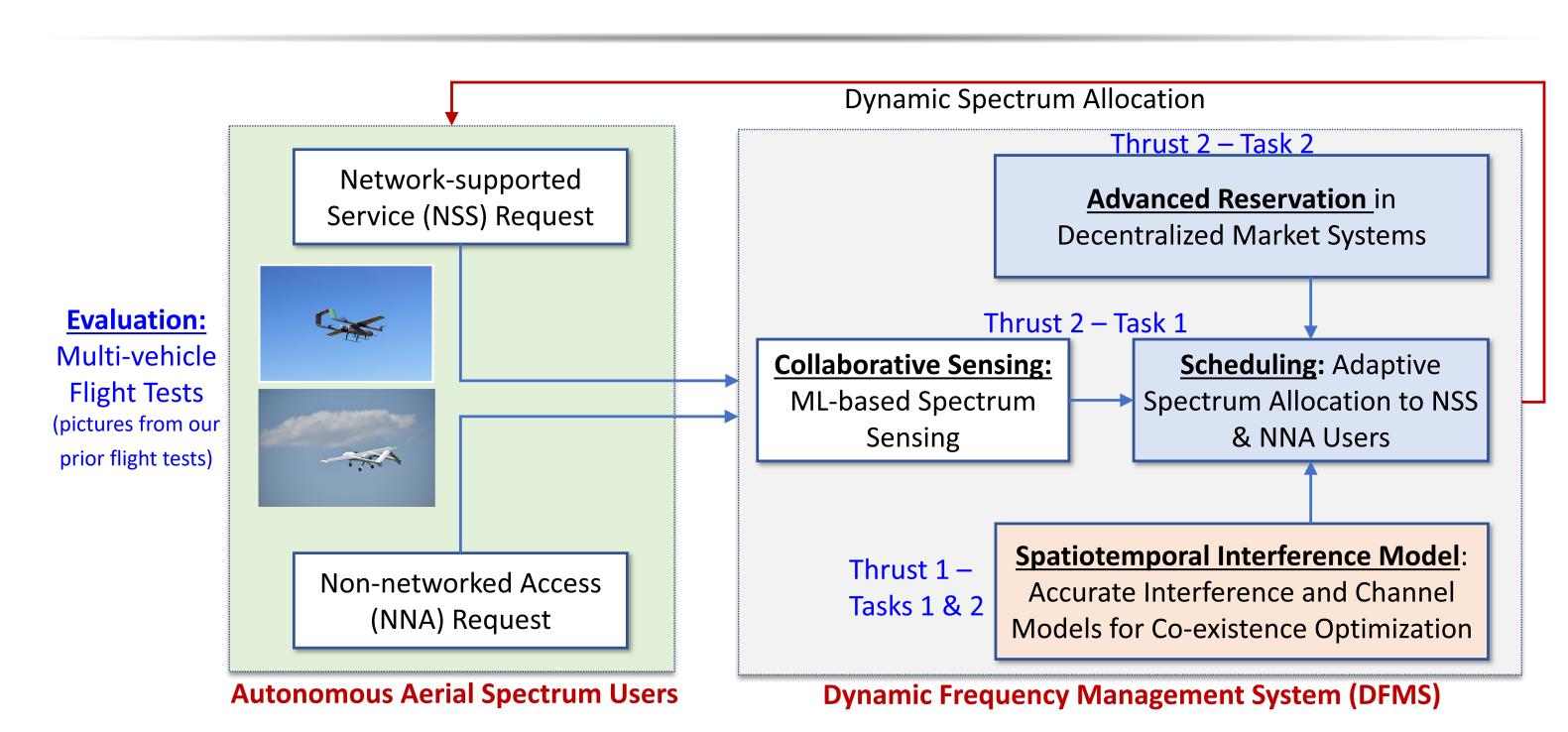


Figure 1: Overview of the proposed research tasks to enable dynamic frequency management systems (DFMS) for autonomous aerial spectrum users.

Research Thrusts

- Thrust 1 Coexistence Optimization for UAS Operations. This thrust is focused on coexistence optimization in the 5030-5091 MHz band, by investigating DFMS design and requirements, building an experimental setup for multi-vehicle flight tests to collect accurate spatiotemporal data, and developing an interference-aware system optimization.
- Thrust 2 Decentralized Spectrum Optimization and Market Systems. This thrust is aimed at developing joint cooperative spectrum sensing and access using ML-based solutions, as well as developing a decentralized spectrum market with advanced reservation within the DFMS architecture.
- Evaluation Plans. Our comprehensive validation and verification plan focuses on testing, evaluating, and refining theoretical developments, which include simulation, hardware-in-the-loop (HiTL) emulation, and actual flight tests using multi-agent aircraft flight tests.

Relationship of this Project to Spectrum Era 4

Our goal is to develop a dynamic frequency management system for providing *time- and location-based licenses* to UAS operators to achieve high spectrum utilization while ensuring interference-protected operation for safety-critical messages. Our framework comprises several key components:

- A comprehensive system and architecture design of the DFMS to enable dynamic spectrum allocation,
- Multi-vehicle flight tests to gather extensive spectrum data, which are crucial for testing and refining spatiotemporal interference and channel models,
- Spectrum situational awareness through adaptive ML-based algorithms trained on collected spectrum data, establishing joint cooperative sensing and access, and ultimately enabling automated spectrum monitoring and enforcement, and
- A decentralized market system with advanced reservation, implementing the "pay-as-you-fly" concept for UAS operators seeking access to interference-protected aviation-grade spectrum in the 5030-5091 MHz band.

Thrust 1: Coexistence Optimization for UAS Operations

To enable interference-protected access to the 5030-5091 MHz band, DFMS will be used for frequency coordination as well as providing dynamic, efficient, and automated (non-manual) access to the band for:

- Non-networked access (NNA): localized flights with the UAV communicates directly with the ground controller via wireless links. These operations are "licensed-by-rules".
- Network-supported services (NSS): using a deployed network infrastructure for information relaying between the GCS and UAV.

Thrust 1: Coexistence Optimization for UAS Operations

Task 1.1: Dynamic Frequency Management System (DFMS) Design. This task is focused on deriving DFMS functionalities and requirements for dynamic and efficient spectrum management for aerial operations.

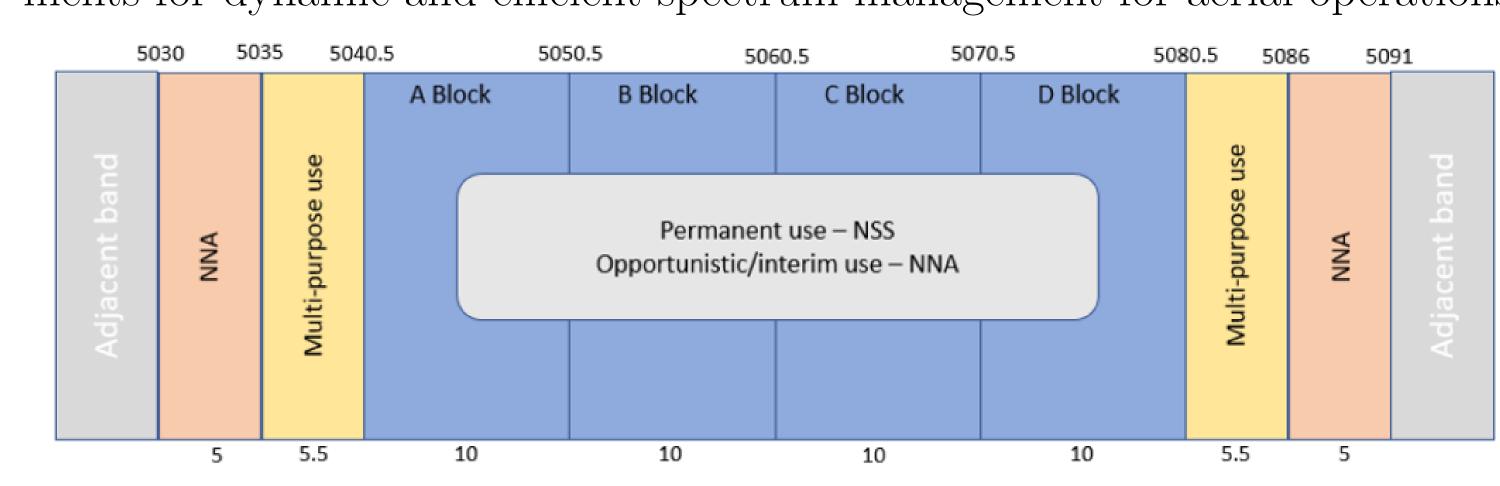


Figure 2: A band plan proposed by the FCC.

DFMS requirements. (i) UAS operators, who operate consistent with their assignment, should be protected from harmful interference, (ii) UAS operators should have flight authorization from the responsible parties within the UTM system (e.g., UAS service supplier (USS)), (iii) UAS operators should follow their assignment and do not cause harmful interference to other protected operations, and (iv) the DFMS entities should participate in decentralized markets to accommodate time- and location-based reservation requests, as well as setting associated spectrum access fees to improve spectrum utilization and avoid spectrum warehousing.

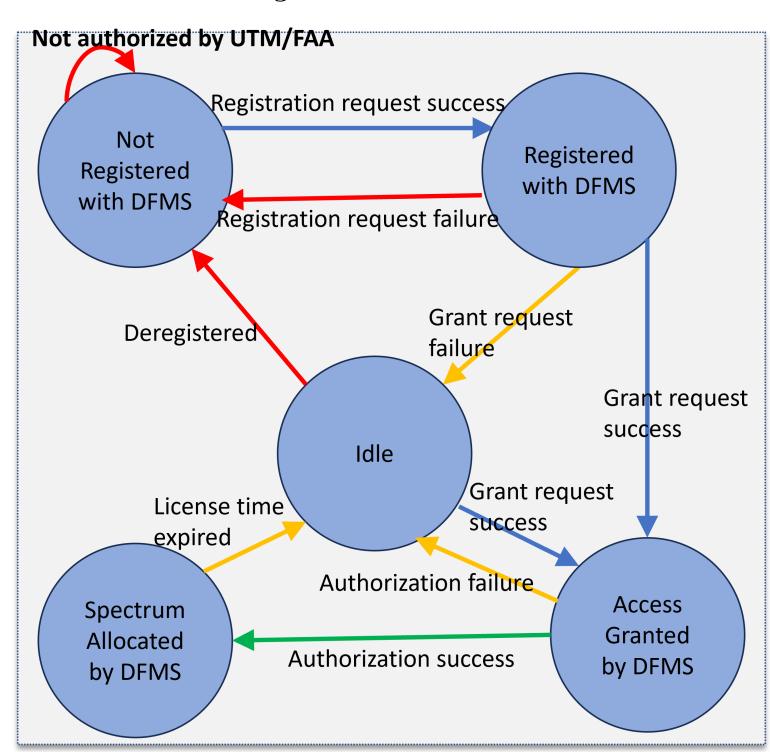


Figure 3: State flow diagram for the interfaces between the DFMS and UAS operator.

Task 1.2: Multi-Vehicle Flight Tests for Channel and Interference Analysis. This task involves building a multi-vehicle experimental setup to gather extensive C-band measurement data. We will use collected data to refine the existing spatiotemporal channel and interference models.

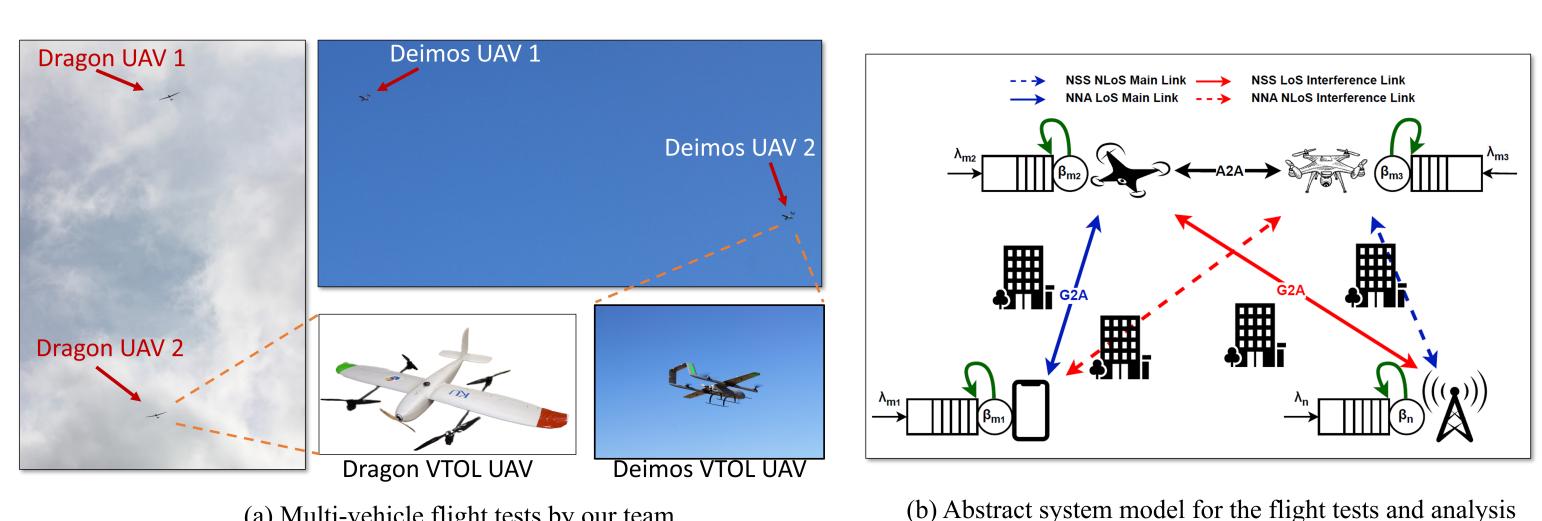
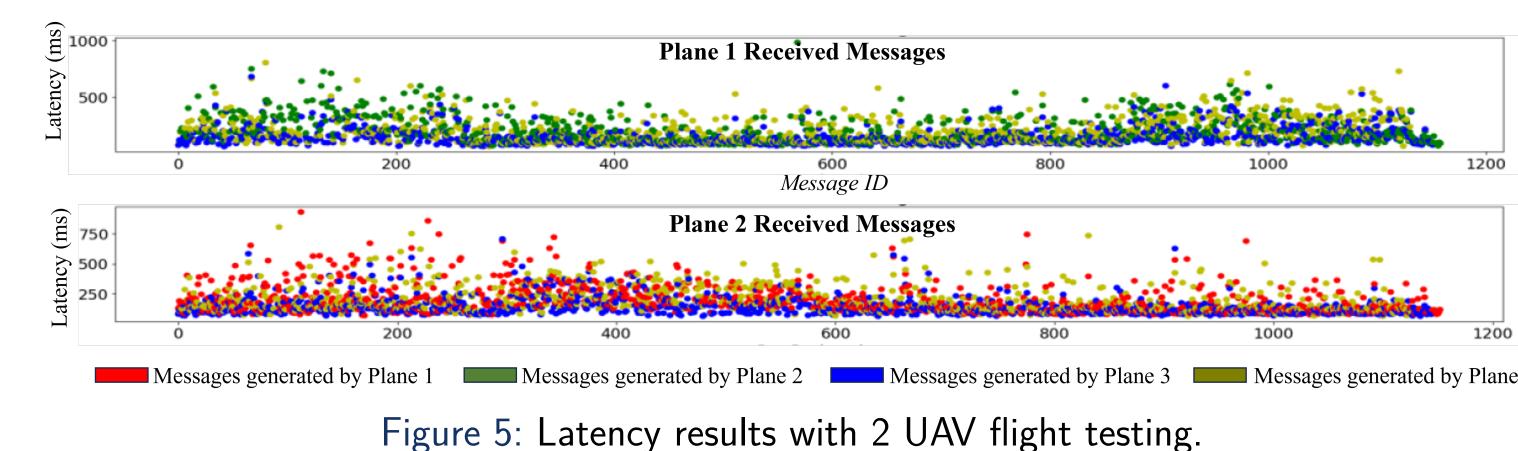


Figure 4: Multi-vehicle flight tests with 2 UAVs for A2A, A2G, and G2A channel and interference measurements.



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Thrust 2: Decentralized Spectrum Optimization and Market Systems

Task 2.1: Joint Cooperative Sensing and Scheduling. In this task, we will develop efficient joint cooperative sensing and scheduling for the C-band spectrum. We develop deep reinforcement learning (DRL) solutions for the DFMS architecture, which takes the spectrum hole predictions as an input. The output of the DNN-based spectrum sensing will be integrated with the RL algorithm to establish a data-driven joint cooperative sensing and scheduling modules trained on collected measurements.

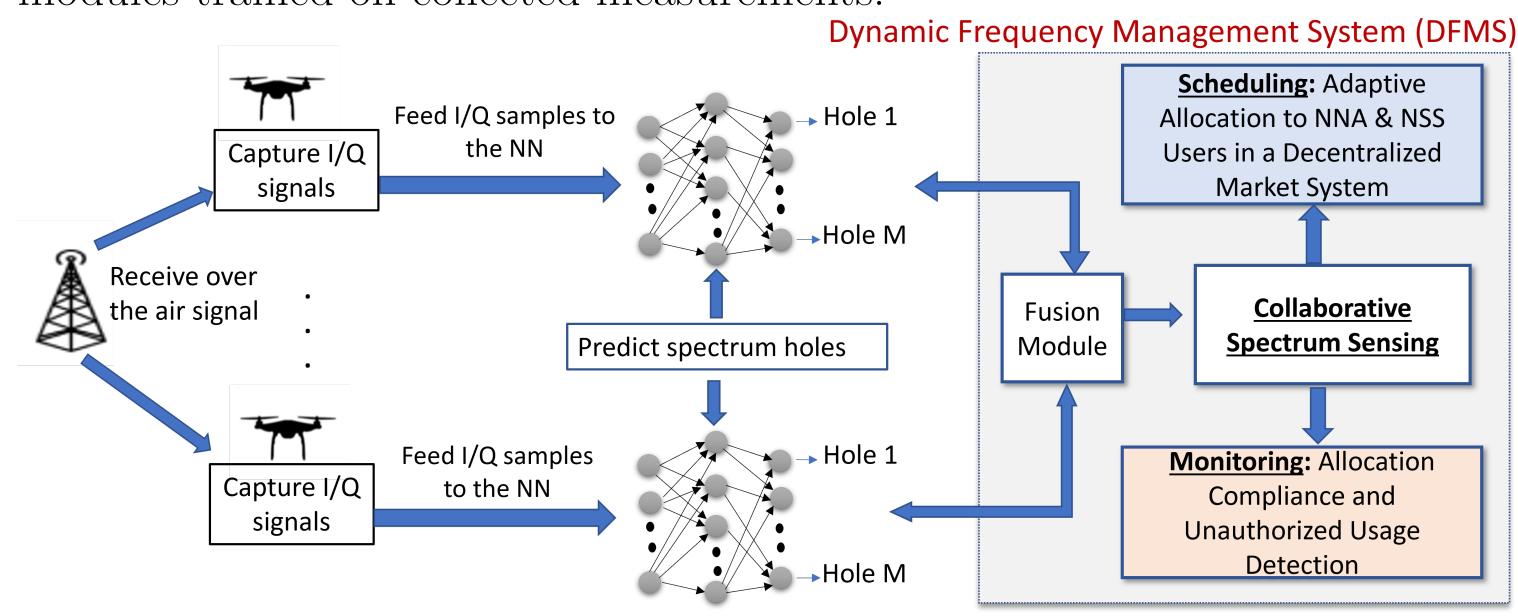


Figure 6: Proposed system model for joint cooperative spectrum sensing and scheduling.

Task 2.2: Decentralized Markets and Advanced Reservation for DFMS. In this task, we integrate engineering technology and economic incentives to model spectrum allocation through decentralized markets. A key requirement for UAVs is an interference-free and reliable CNPC link throughout the flight, motivating an *advance reservation system (ARS)*. We will model spectrum trading over two horizons: (i) long-horizon trades made in advance for operational planning, and (ii) short-horizon trades made near flight time to address demand fluctuations and supply availability. These will be formulated as a two-stage oligopoly competition with standardized goods.

Evaluation and Demonstration Plans

- (1) Software-in-the-loop (SiTL) emulation that integrates the flight simulator ArduPilot and NS-3 network simulator.
- (2) Hardware-in-the-loop (HiTL) Emulation and Flight tests that enable us to "mix and match" the actual flight tests with the HiTL flight tests.

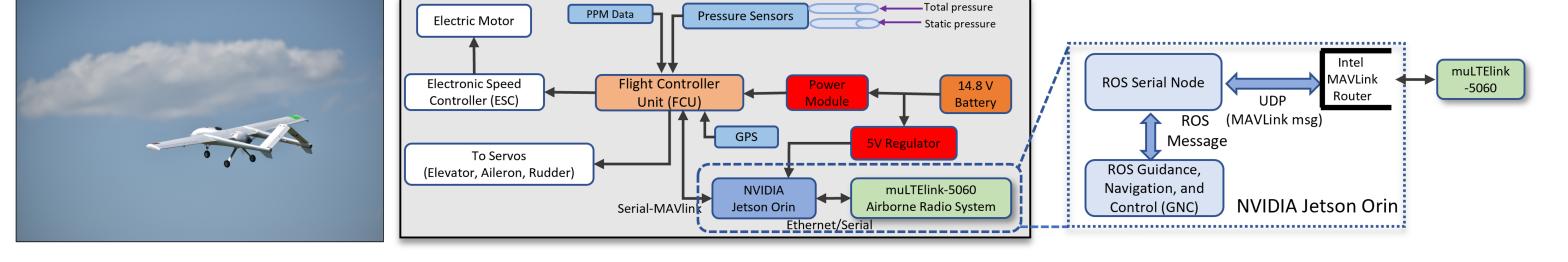


Figure 7: Internal system components for UAV flight testing.

Broader Impacts

- Spectrum RF Database. Our experiments will provide large-scale spectrum dataset for aerial operations in C-band using automated, programmable, and multi-vehicle flight tests.
- Policy Impacts. Technical spectrum studies in the C-band are pivotal for informing policy decisions regarding spectrum management, allocation, and regulation by the FCC, NTIA, FAA, and NASA.
- Bridging Spectrum Engineering, Economics, and Aerospace Engineering. This project introduces a unique symbiosis between the wireless communication and spectrum engineering with the aerospace engineering and economics communities.

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