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Resilient Cyber-Physical Power Grids with Large-Scale UAV Integration

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Dear Editor,

The low-altitude economy is witnessing exponential growth, fueled by the widespread implementation of unmanned aerial vehicles (UAVs), brings a fundamental paradigm shift for power systems. As a novel class of active mobile agents, UAVs exhibit spatiotemporal characteristics with operation in stochastic three-dimensional space, high-frequency mobility, and mission-driven energy consumption.

These unique operational characteristics introduce multiple impacts on power grids. The large-scale integration of UAVs presents considerable operational challenges. Driven by mission urgency and environment variables, dynamic load centers are created characterized by UAVs' fast charging or battery swapping. Without coordination, this spatiotemporal heterogeneity may exceed local grid capacity. Currently, the low-altitude transport network and the power grid operate as interdependent but decoupled systems, creating risks of cross-domain functional degradation and cyber-physical vulnerabilities.

However, UAVs possess latent capabilities across sensing, communication, and energy domains. Beyond functioning as flexible resources for demand response during normal conditions, they act as critical resilience assets during emergencies. UAVs can extend grid observability, bridge severed communication links, and serve as airborne mobile power sources to restore isolated loads. The critical gap lies in the absence of a unified architecture to coordinate these diverse capabilities.

This letter analyzes the impacts of large-scale UAVs on power grids and proposes a novel framework for the UAV-Grid Cyber-Physical System (CPS). By establishing a three-layer architecture bridging physical resources, cyber perception, and decision-control logic, we aim to transform UAVs from stochastic airborne loads into dispatchable, resilient assets for the future smart grid.

MULTIDIMENSIONAL IMPACTS OF LARGE-SCALE UAV INTEGRATION: CHALLENGES, CAPABILITIES, AND RISKS

The massive integration of UAVs introduces a complex cyber-physical coupling interface to the power grid.[1] This section analyzes the multidimensional impacts of this integration.

Operational Challenges: Spatiotemporal Heterogeneity and Dynamic Load Behavior

The impact of UAV integration stems from its mission-driven load morphology, which forms a novel spatiotemporal heterogeneous load that challenges grid stability. UAVs operate in unconstrained mobility environments, subject to environmental variables such as wind speed and temperature, as well as airspace regulations.[2] These factors significantly alter energy consumption rates and flight ranges, making charging demands difficult to forecast. Consequently, the spatiotemporal distribution of charging loads becomes uncertain, complicating the load prediction required for optimal dispatch.

Furthermore, charging or battery swapping behaviors of UAV fleets at specific nodes can form highly dynamic load centers. Such uncoordinated load may cause overloads and instability.[3] This issue is exacerbated by the highly distributed nature of UAV access points, which renders traditional centralized control methods ineffective.

These operational characteristics necessitate a paradigm shift in grid planning and infrastructure development. Traditional capacity planning, reliant on historical residential and industrial data, is insufficient for the emerging low-altitude economy. Planners must account for spatial constraints and the coupling between flight routes and power capacity.[4] The absence of coordinated planning between the charging network and the distribution grid risks creating structural bottlenecks that hinder grid stability and transport efficiency.

Latent Capabilities: Integrated Sensing, Communication, and Energy

Despite these operational stresses, UAVs possess intrinsic capabilities that can serve as versatile grid assets if properly coordinated. In terms of situational awareness, UAVs significantly extend power system observability. Equipped with high-precision sensors and edge computing, they facilitate the autonomous inspection of transmission lines and critical equipment.[5] In post-disaster scenarios, UAVs provide dynamic situational awareness by monitoring damaged grid topology and ground traffic, supplying real-time data to guide recovery strategies where ground sensors and communication networks have failed.[6]

UAVs can also function as critical resilience assets during emergencies. When ground networks are compromised, UAVs can be rapidly deployed to construct aerial relay networks.[7] This restoration re-establishes a bidirectional link, enabling the transmission of dispatch data and the execution of critical control commands. Crucially, UAVs carrying energy storage modules can bypass damaged ground routes to serve as airborne power sources. By delivering energy to isolated areas, they enable rapid power recovery for critical loads such as hospitals and base stations, significantly enhancing system resilience.

Additionally, UAV fleets hold significant potential for flexible demand response. Transitioning from passive loads to controllable resources, UAVs can participate in grid optimization by integrating charging schedules with dispatch signals. This allows fleets to adjust charging timing and locations in response to dynamic electricity prices. This enables UAVs to contribute to load shifting and renewable energy absorption, transforming them into tools for active distribution network management.

Systemic Risks: Cyber-Physical Vulnerabilities

The deep coupling of the low-altitude transport network and the power grid

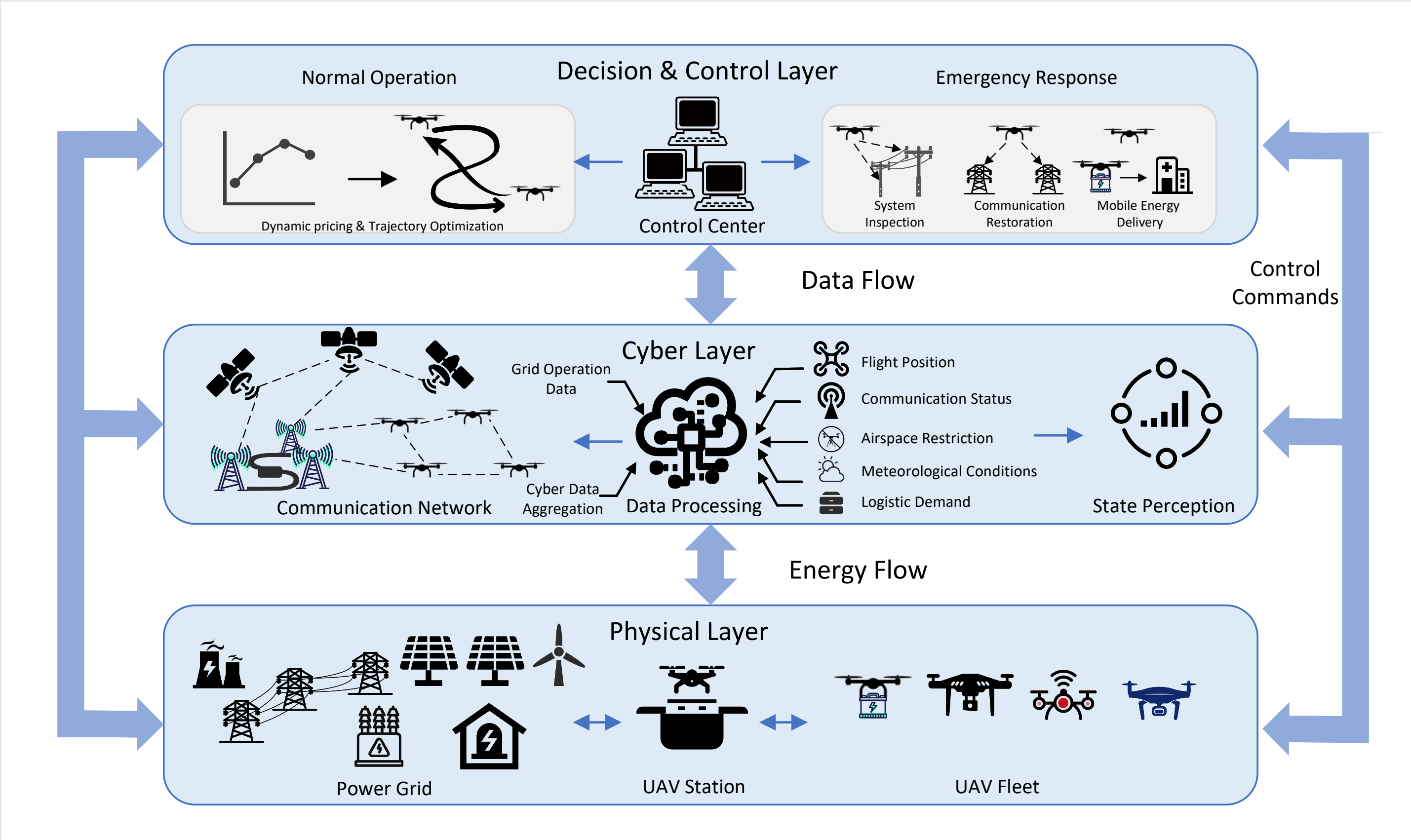

Figure 1. Framework for UAV-Grid Cyber-Physical System.

introduces critical vulnerabilities, where the strict functional interdependence between energy and data flows creates pathways for cross-domain capability degradation.[8] This fragility manifests as a negative feedback loop: a physical grid fault can de-energize UAV charging or communication nodes, grounding fleets and blinding the grid's situational awareness, thereby delaying fault diagnosis required for restoration. Conversely, a communication outage paralyzes the command link necessary for dynamic dispatch, degrading routine inspection capabilities and allowing minor physical failures to propagate into major infrastructure failures.

Additionally, the massive integration of UAVs may bring cybersecurity attack to the smart grid. As connected IoT devices, UAV control systems represent potential entry points for cyber intrusions. Without robust security protocols, compromised UAVs could be manipulated to disrupt grid operations or serve as gateways for attackers to access the power network, highlighting the critical need for a secure, unified control architecture.

FRAMEWORK FOR THE UAV-GRID CYBER-PHYSICAL SYSTEM

To address the challenges of spatiotemporal heterogeneity and leverage the latent capabilities of UAV fleets, we model the interaction between the low-altitude transport network and the power grid as a UAV-Grid Cyber-Physical System. Unlike existing coordination models that view UAVs as passive loads or focus on UAV routing optimization, this framework establishes a deep bidirectional cyber-physical coupling. As illustrated in Figure 1, the framework comprises three integrated layers that facilitate energy-information-control interconnection, transforming stochastic airborne loads into dispatchable assets through a unified architecture.

Physical Layer

As the foundation of the framework, the Physical Layer encompasses the energy flows and physical entities. This includes the distribution topology and distributed energy resources on the grid side, and UAV fleets characterized by flight mechanics and battery constraints. The critical coupling mechanism is anchored by multi-functional smart interface nodes, such as smart streetlights, wireless charging pads and mobile charging vehicles, which integrate charging piles and battery swapping stations. which integrate charging nests and battery swapping stations. These nodes serve as physical intersections where UAV flight envelopes interact with grid power flow constraints. Furthermore, this layer supports bidirectional energy interaction, enabling UAVs to function as mobile storage units that physically transport energy to isolated grid sections during infrastructure failures. In addition, UAVs are subject to strict energy consumption constraints to ensure flight safety.

Cyber Layer

Bridging the physical entities, the Cyber Layer relies on a multi-dimensional hybrid communication architecture to ensure connectivity. The communication network integrates optical fiber and base stations, satellite links for wide-area coverage, and aerial mesh networks for UAV fleets. This layer aggregates heterogeneous information to construct state perception. It synthesizes grid operation data, flight position, and communication status, while incorporating datasets such as airspace restrictions, meteorological conditions, and logistics demand. The layer processing these inputs into actionable cross-domain knowledge, ensuring system observability and fleet controllability.

Decision and Control Layer

The Decision and Control Layer embodies the deep cyber-physical coupling mechanism of the system, executing a unified control logic where physical states dictate cyber decisions and cyber algorithms drive physical actuations. As illustrated in Figure 1, the energy-information-control interactions are inherently bidirectional. The energy flow encompasses both UAV charging and UAV carrying energy storage discharging, while data flow involves real-time state information uploading along with control instruction downloading. This coupling is manifested primarily through energy-mobility coordination during normal operations, where the system intertwines physical power flow constraints with cyber routing algorithms. By broadcasting cyber-calculated dynamic prices, it physically reshapes UAV flight trajectories and charging behaviors to alleviate grid congestion. Furthermore, during emergencies, the layer activates cyber-physical resilience restoration strategies that intensify this coupling by closing the loop between communication recovery and physical repair. A holistic recovery process is established by utilizing UAV fleets for dynamic situational awareness to assess topology damage, deploying UAVs to bridge severed communication links to restore cyber command capabilities, and subsequently coordinating the physical transport of emergency resources, such as mobile energy modules, to energize critical isolated loads. This integrated approach ensures that the restoration of cyber connectivity directly enables the physical repair of the grid, achieving a synergistic enhancement of total system resilience.

CONCLUSION

The integration of large-scale UAVs presents a paradigm shift where the spatiotemporal stochasticity of UAV fleets challenges traditional grid stability. This letter addresses this dichotomy by proposing a novel framework for UAV-Grid Cyber-Physical System, which integrates physical resources, cyber perception, and decision-control logic into a unified architecture. This framework transforms UAVs from dynamic loads into dispatchable resources capable of providing multi-dimensional resilience support. Ultimately, this symbiotic approach not only mitigates the risks of cross-domain functional degradation but also establishes a new frontier for enhancing grid resilience. Looking ahead, the large-scale deployment of this framework necessitates coordinated advancements in regulatory standardization, market mechanisms and privacy-preserving protocols to ensure a secure and sustainable cyber-physical system.

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DECLARATION OF INTERESTS

The authors declare no competing interests.