

Digital Twin-Based Energy Management for Agricultural UAVs: A Survey on Power Modeling, Battery Health, and Event-Driven Decision Support

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ABSTRACT

Precision agriculture increasingly relies on unmanned aerial vehicles (UAVs) for tasks such as pesticide spraying, where energy management directly determines mission safety and efficiency. This study synthesizes current digital twin-based energy management approaches for agricultural UAVs, examining four interconnected research domains: multi-rotor power consumption modeling, battery state-of-health (SoH) estimation, energy-aware flight planning, and event-driven decision support systems. Through a critical analysis of 29 sources spanning academic publications and industrial patents, we identify four fundamental research gaps: (1) the absence of dynamic payload mass reduction in energy models, (2) the lack of wind perturbation-integrated point-of-no-return (PNR) decision mechanisms, (3) insufficient integration of battery SoH into real-time energy estimation for agricultural contexts, and (4) the absence of integrated event-driven re-simulation within digital twin architectures. A cross-examination of these deficiencies reveals that existing studies address these variables in isolation, whereas their operational coupling is what determines real-world mission reliability. Accordingly, a unified digital twin framework that simultaneously integrates dynamic payload modeling, wind-aware PNR logic, SoH-informed energy estimation, and event-triggered re-simulation represents the primary unmet research need for safe autonomous agricultural UAV operations.

Keywords: agricultural UAVs; battery state of health; digital twin; energy management; point of no return; software-in-the-loop simulation

1. INTRODUCTION

The growing demand in precision agriculture has rendered Unmanned Aerial Vehicles (UAVs) an indispensable component of modern agricultural operations. Unlike conventional agricultural machinery, UAVs can perform targeted interventions on rugged terrains with minimal human intervention. Comprehensive literature reviews reveal that UAV-based systems provide measurable improvements over traditional ground vehicles in terms of spraying efficiency, vegetation monitoring accuracy, and area coverage speed [1], [2]. Flight path adherence, payload dynamics, and energy consumption are interconnected variables that determine mission success in pesticide spraying—a high-stakes agricultural application [3].

Energy management represents one of the most significant factors limiting the widespread adoption of Agricultural UAVs. Battery-powered multi-rotor platforms, which dominate the pesticide application segment, are preferred for their hovering and maneuverability capabilities; however, they operate within a structurally limited energy budget. The relationship between payload mass, rotor thrust, and energy consumption is non-linear; in spraying missions, this relationship undergoes continuous change as the chemical tank depletes during flight [4]. Furthermore, environmental variables such as wind impact create dynamic deviations from pre-planned energy consumption profiles, rendering static mission planning insufficient for real-world operations

[5]. These constraints emphasize a fundamental requirement for real-time and adaptive energy management frameworks capable of responding to mid-mission state changes.

Digital Twin (DT) technology emerges as a promising paradigm to address these requirements. By maintaining a high-fidelity virtual replica of a physical asset, the DT enables predictive reasoning, anomaly detection, and real-time decision support through bidirectional data integration [4]. Within the context of UAV systems, Digital Twins can be integrated with Software-in-the-Loop (SITL) environments to validate energy models, test decision logic, and simulate failure scenarios before and during actual deployment. However, despite the maturity of Digital Twin frameworks in industrial and Cyber-Physical System (CPS) domains, their application in energy-aware Decision Support Systems for Agricultural UAVs has not yet been sufficiently explored in the literature.

This review systematically examines the current state of research in four interconnected key areas: (i) energy modeling and battery management for multi-rotor UAVs, (ii) energy-aware flight planning and route optimization, (iii) Digital Twin and SITL integration methodologies, and (iv) event-driven Decision Support Systems and fault tolerance mechanisms. Through this structured analysis, the review identifies critical gaps in the literature. In particular, the absence of integrated frameworks that combine payload depletion dynamics modeling, battery SoH estimation, Point of No Return (PNR) based decision logic, and event-triggered re-simulation within a unified Digital Twin architecture for Agricultural UAVs is highlighted.

These four research gaps are not independent; rather, they form a structurally coupled set of deficiencies. Dynamic payload mass reduction, wind-integrated PNR decision logic, battery SoH estimation, and event-driven re-simulation are all interdependent components that must be addressed simultaneously within a unified Digital Twin architecture to achieve reliable autonomous agricultural UAV operations (Figure 1).

Interconnection of Research Gaps in Agricultural UAV Energy Management

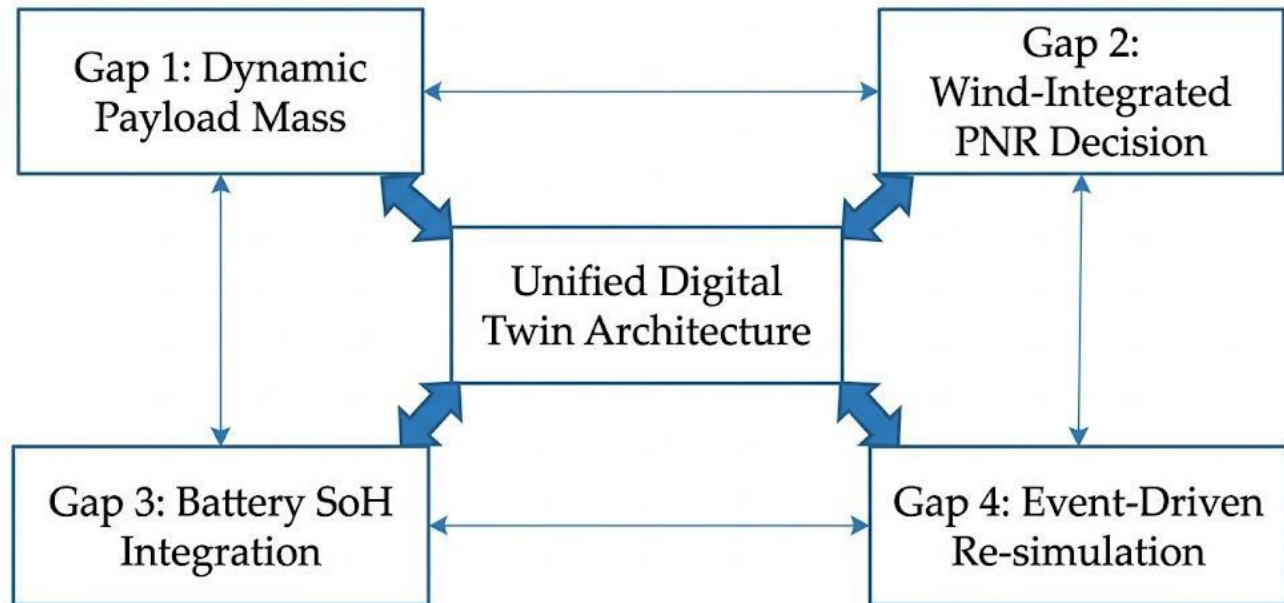


Figure 1. Interconnection of the four research gaps identified in this survey and their convergence toward a unified Digital Twin architecture for agricultural UAV energy management.

The remainder of this paper is organized as follows: Section 2 presents energy modeling and battery management approaches. Section 3 examines flight planning and route optimization strategies. Section 4 addresses Digital Twin and SITL integration methods. Section 5 discusses event-driven Decision Support Systems and fault tolerance systems. Section 6 identifies research gaps and outlines future work directions.

2. ENERGY MODELING AND BATTERY MANAGEMENT FOR UAVs

Energy management in multi-rotor UAVs is a fundamental engineering problem that directly dictates mission reliability. Limited battery capacity is the primary constraint on the operational lifespan of these platforms; therefore, accurate modeling of energy consumption is critical for both mission planning and operational safety. This section provides a comparative analysis of power consumption models, battery discharge and SoH models, and flight endurance estimation approaches.

2.1 Power Consumption Models

The total power consumption in multi-rotor UAVs comprises the sum of induced power, profile power, and parasitic power components. Each component reflects distinct physical mechanisms and varies according to flight conditions.

Hwang et al. [9] developed a practical endurance estimation method encompassing both hover and steady-level forward flight conditions. The study proposes a user-friendly model by correlating thrust, efficiency, and battery discharge with parameters

derivable from manufacturer specifications. Specifically, the opposing effects of drag coefficient and payload weight on endurance were experimentally demonstrated, validating the model with an average error rate of 2.3%. It was observed that the optimal flight speed increases with higher payload mass, whereas it decreases as the drag coefficient rises.

Gong et al. [10] presented a closed-form mathematical framework that generalizes single-rotor UAV power consumption models to multi-rotor platforms. These models, separately derived for forward flight, vertical climb, and vertical descent scenarios, were validated through extensive experiments using the DJI M210 platform, analyzing over 7,000 valid power-speed data points. Investigating the impact of the number of rotors on energy consumption, the study demonstrated that increasing the rotor count reduces power consumption in low-speed regimes where induced power loss is dominant.

Matras et al. [11] developed a physics-based power model treating induced, profile, and parasitic losses as independent subsystems. A notable contribution of this work is the inclusion of rotor interactions, a factor neglected in most prior studies. Experiments conducted on the DJI Phantom 4 platform revealed that a 13% power saving could be achieved at a forward flight speed of approximately 8 m/s compared to hovering.

A common limitation of existing studies is that power models are constructed under the assumption of a static payload mass. In spraying missions, the payload depletion dynamics resulting from the depletion of the chemical tank is not addressed in real-time by any current models. Furthermore, in Variable Rate Application (VRA) systems, the flow rate control synchronized with the UAV's instantaneous flight speed causes the mass reduction profile to deviate significantly from constant flow assumptions.

2.2 Battery Discharge and SoH Models

Accurate modeling of battery performance is indispensable for defining mission planning and safe operational boundaries. LiPo batteries are the predominant power source for multi-rotor UAVs due to their high energy density and low weight; however, their discharge behavior varies significantly based on load type, temperature, and aging.

Di Nisio et al. [6] conducted an experimental study to model LiPo battery discharge under variable power loads. It was shown that model parameters obtained from constant-power characterization tests could be successfully generalized to variable power discharge conditions. The inclusion of only three tunable parameters allows for rapid calibration across different battery packs. The normalized estimation error remained below 0.7%, supporting the model's viability for operational UAV scenarios. However, the study excluded the effects of battery aging and environmental temperature fluctuations on model parameters.

Schacht-Rodriguez et al. [8] reviewed battery state-of-health estimation approaches for UAV endurance prediction, including model-based and data-driven methods. The review underscores the growing importance of data-driven approaches for capturing nonlinear degradation behavior associated with cycle count and temperature variation. However, a comprehensive study addressing state-of-health estimation specifically under the unique charge-discharge profiles of agricultural UAVs is absent from the reviewed literature.

Arsalan et al. [12] explored the energy-efficient task allocation problem within the FD-IoD architecture by applying the DT paradigm. This framework, which prioritizes tasks based on real-time battery levels, reported up to a 40% improvement in energy

efficiency compared to baseline systems through a decentralized decision-making approach. Nevertheless, the study lacks battery characterization specific to agricultural spraying scenarios, and the evaluation was limited to simulation environments without validation on physical UAV hardware.

2.3 Flight Endurance Estimation

Flight endurance estimation constitutes the fundamental input for mission planning and plays a direct role in defining safe operational boundaries.

Schacht-Rodriguez et al. [7] developed a mission planning strategy based on flight endurance for multi-rotor UAVs. This study, conducted on a hexarotor platform, introduced a Prognosis Module that calculates the Remaining Mission Time by considering battery SoC and SoH. The impact of actuator failures on energy consumption during the mission was also evaluated, addressing the fault tolerance dimension of the energy model. A prominent contribution of this work is the provision of a comprehensive framework that integrates mission planning with energy prognosis; however, the model operates under the assumption of a constant payload mass and does not reflect the dynamic mass changes inherent in spraying missions.

Hwang et al. [9] calibrated endurance estimation through experimental measurements under various combinations of drag coefficients and payload weights. This approach models battery discharge as an iterative process and assumes a linear voltage decrease under constant power discharge conditions. The estimation results were compared with actual flight data, demonstrating the utility of the method during the preliminary design phase.

Table 1 provides a structured overview of all reviewed studies across the four research dimensions identified in this survey. The absence of checkmarks across Payload Dynamics, Battery SoH, Wind Integration, and Event-Driven columns confirms that no existing work addresses all four dimensions simultaneously.

Table 1. Comparative analysis of reviewed studies across key research dimensions

Study / Focus	Energy Model	Payload Dyn.	Battery SoH	Wind Integr.	DT/SITL	PNR/RTH	Event-Driven	Validation
[1] Toscano et al.	–	–	–	–	–	–	–	Review
[2] Guebsi et al.	–	–	–	–	–	–	–	Review
[3] Güneş & Hasegawa	–	–	–	Partial	–	–	–	Field+Sim
[4] Dihan et al.	–	–	–	–	✓	–	–	Review
[5] Safaeinejad et al.	Empirical	–	–	–	–	–	–	Field Exp.
[6] Di Nisio et al.	–	–	Partial	–	–	–	–	Lab Exp.
[7] Schacht-Rodríguez	Physics	–	✓	–	–	Partial	–	Simulation
[8] Schacht-Rodríguez	–	–	✓	–	–	–	–	Review
[9] Hwang et al.	Physics	Partial	–	–	–	–	–	Field+Sim

[10] Gong et al.	Physics	-	-	-	-	-	-	Field Exp.
[11] Matras et al.	Physics	-	-	-	-	-	-	Field+Sim
[12] Arsalan et al.	-	-	-	-	✓	-	Partial	Simulation
[13] Escobar & Pereira	Physics	-	-	-	-	-	-	Sim+Field
[14] Di Franco & Buttazzo	Empirical	-	-	-	-	-	-	Field Exp.
[15] Hung et al.	-	-	-	-	-	✓	-	Field Exp.
[16] Li et al.	-	-	-	✓	-	-	-	Field Exp.
[17] Nguyen et al.	-	-	-	-	-	✓	-	Field Exp.
[18] Teschner et al.	-	-	-	-	✓	Partial	-	SITL+HITL
[19] Oña et al.	-	-	-	Partial	✓	-	-	Simulation
[20] Peng & Chen	-	-	-	-	✓	-	Partial	Real Flight
[21] Chamorro et al.	Physics	-	-	Partial	✓	-	-	Sim+Field
[22] Aliane	-	-	-	-	Partial	-	-	Review
[23] Steindl et al.	-	-	-	-	-	-	✓	Case Study
[24] Zhang et al.	-	-	-	-	-	-	✓	Simulation
[25] Chen et al.	-	-	-	-	-	-	✓	Simulation
[26] Qadir et al.	-	-	-	-	✓	-	Partial	Review
[27] Hall et al.	-	-	-	-	✓	-	-	Sim+Field
[28] Yang (WIPO)	Empirical	-	-	✓	-	✓	-	Patent
[29] Lei/Autel	Physics	-	-	✓	-	✓	-	Patent

3. FLIGHT PLANNING AND ROUTE OPTIMIZATION

Flight planning in Agricultural UAV operations should be evaluated not merely as a geometric coverage problem, but as a multidimensional optimization problem that simultaneously addresses interconnected variables such as energy constraints, environmental disturbances, and safe return requirements. This section provides a comparative analysis of energy-aware area coverage paths, the impact of wind fields on spraying performance, and return-to-home mechanisms.

3.1 Energy-Aware Area Coverage Path Planning

Area Coverage Path Planning (CPP) is the process of calculating a flight trajectory that covers the entirety of a specified region. While conventional CPP approaches consider only geometric constraints, contemporary studies adopt energy consumption as a primary optimization criterion.

Escobar and Pereira [13] presented a novel CPP approach that directly minimizes energy consumption using a Mixed-Integer Linear Programming (MILP) framework and an energy model. A notable finding of the study is that the energy-based cost function significantly reduces the MILP solution time compared to distance-based approaches. This method, validated through

simulations and real-world experiments, achieved significant improvements in computation time for high-complexity problems. Nevertheless, the study acknowledges that this approach is not yet suitable for online planning and that standard flight controller constraints in commercial UAVs complicate its implementation.

Di Franco and Buttazzo [14] proposed an energy-aware CPP algorithm based on an energy model derived from real measurement data. This algorithm calculates a flight path that simultaneously satisfies constraints such as desired spatial resolution, available energy, and maximum camera sampling period. Validated through real flight experiments, the model reported that flight time estimation converged to actual values with a 5% relative error, and energy estimation with a 2% relative error. This study provides a pioneering analysis of the trade-off between energy consumption and spatial resolution; however, the model relies on a static payload mass assumption and excludes wind impact.

Neither study incorporates the payload depletion dynamics in spraying missions into the energy model. An approach where the changing mass—as the tank empties during the mission—is reflected in real-time route optimization is not found in the reviewed literature.

3.2 Wind Impact and Spraying Performance

The wind field in a UAV's operational environment simultaneously governs two interdependent phenomena: spraying performance and motor power consumption. Li et al. [16] conducted a comparative field study on multiple DJI Agras UAV models, demonstrating that rotor downwash is the primary determinant of pesticide droplet penetration into crop canopies. Larger-rotor models achieved substantially higher droplet densities in middle and lower leaf layers, and all UAV models yielded higher pesticide utilization rates than conventional boom sprayers.

Beyond horizontal crosswinds, vertical wind disturbances can introduce additional uncertainty into power demand and altitude control for small UAVs operating over uneven terrain and vegetation. Because such disturbances alter the aerodynamic environment in real time, they can cause deviations from pre-planned power profiles and complicate endurance estimation. This coupling between wind perturbation and instantaneous power draw has not been captured by any energy model reviewed in the literature.

These observations highlight a critical modeling gap: the dynamic effect of environmental wind perturbations on instantaneous energy consumption remains an unmodeled variable in the current literature. Incorporating wind field data as a real-time input into energy budget calculations is essential for constructing accurate PNR thresholds and endurance estimates in operational agricultural UAV missions.

3.3 Return-to-Home Mechanisms

Return-to-home (RTH) mechanisms encompass the systems that ensure the UAV safely returns to the takeoff point at the end of a mission or when a critical energy threshold is reached. Three interconnected problems stand out in this field: energy sufficiency assessment, navigation accuracy, and route replanning.

Hung et al. [15] conducted an experimental study evaluating the RTH landing accuracy of four different DJI UAV models in forested terrain. Each model was tested under various weather conditions across 30 missions; it was revealed that GNSS receiver accuracy, the visual recognition algorithm of the downward-facing camera, and collision avoidance sensors directly impact landing precision. While the study substantiates the criticality of RTH mechanisms in obstacle-laden environments, it does not address the relationship between energy status and the safe landing decision.

Nguyen et al. [17] achieved a landing precision of approximately 10 cm using UWB and optical flow fusion. However, the relationship between these navigation methods and the energy budget was not addressed. Incorporating the energy cost of UWB-based positioning into PNR calculations is considered a research direction that could enhance operational reliability against 'double crisis' scenarios.

An energy-threshold-based return decision mechanism is addressed in a patent study by Yang [28]. The return direction and path are calculated based on the UAV's instantaneous energy level and position; the return decision is determined dynamically according to environmental conditions rather than a fixed threshold. A particularly noteworthy aspect is that the return simulation accounts for wind direction: a warning is issued when the initial energy drops to half in tailwind conditions, whereas this threshold is adjusted to one-third in headwind conditions. This approach can be considered the closest industrial application of PNR logic.

Lei [29] proposes a complementary method for estimating the minimum power consumption required for a UAV to return from its current position to the home point. Unlike the fixed-threshold trigger typical of commercial RTH systems, this mechanism dynamically calculates the energy required for return based on instantaneous position, altitude, and power draw. Taken together, the approaches of Yang [28] and Lei [29] represent the closest industrial analogues to an academically rigorous PNR framework; however, neither has been validated through peer-reviewed methods, and both omit battery SoH degradation, dynamic payload mass changes, and agricultural spraying-specific operating profiles.

4. DIGITAL TWIN AND SITL INTEGRATION

Building upon the DT framework defined in Section 1, this section examines how such architectures are implemented in practice through Software-in-the-Loop (SITL) environments. Integrating DTs with SITL offers a robust infrastructure for validating energy models and testing failure scenarios without physical hardware.

4.1 Digital Twin in Agricultural Applications

The utilization of Digital Twins in agricultural fields is an emerging research area. Teschner et al. [18] developed a UAV-based Digital Twin system designed to protect agricultural areas from wildlife attacks. In this study, a virtual replica of a PixHawk-based multi-rotor UAV and an environmental sensor network was created on the Gazebo simulator; the software development process was accelerated by concurrently utilizing SITL and HITL simulation methodologies. The system's state-machine-based control architecture triggers an automatic return-to-base maneuver if the battery warning threshold is exceeded. However, the study does not focus on energy consumption modeling; the battery threshold is utilized only as a simple trigger condition.

Oña et al. [19] presented a methodology based on the integration of SITL and Digital Twin to optimize flight planning for orthophoto mosaic production in precision agriculture. By combining the Gazebo simulator, a digital model of a multi-rotor

UAV, and a digital terrain model, flight missions were tested in a virtual environment under different overlap configurations and wind conditions. Nonetheless, the study does not correlate flight planning with energy management or battery status.

Peng and Chen [20] developed an online Digital Twin-based anomaly detection system for the tilting motor of a fixed-wing UAV. Motor Digital Twins, created via the Hybrid Observer/Kalman Filter Identification method, were used as reference models for healthy system dynamics; dynamic error thresholds were defined based on error distributions calculated from real flight data. In validation performed on real flight test data, a diagnostic accuracy of over 90% was achieved. However, the study focuses on a fixed-wing platform, and its direct transferability to multi-rotor spraying UAVs is limited.

4.2 SITL Simulation Methodologies

SITL simulation is a widely adopted development methodology in the contemporary open-source UAV ecosystem, allowing for the execution of UAV control software in a virtual environment without the requirement for physical hardware.

Chamorro et al. [21] developed an open-source SITL approach that realistically models challenging weather conditions at high altitudes and in urban settings. Integrating the ROS middleware, the Gazebo simulator, and the ArduPilot autopilot, this study modeled wind perturbation as an external force along the Z-axis; calibration was performed using aerodynamic constants derived from real flight data. In two scenarios conducted in Quito, the position error remained below 10% for average trajectories of 150 m. This study is significant as it substantiates that realistic SITL simulation functions as a bridge during the transition to actual field operations.

4.3 Open-Source Autopilot Systems

Open-source autopilot systems constitute the fundamental infrastructure for UAV software development processes in research and educational environments.

Aliane [22] provided a comprehensive comparison of prominent open-source UAV autopilots in terms of hardware compatibility, software features, and communication protocols. It was demonstrated that ArduPilot and PX4 offer the most robust support for SITL and HITL simulation tools, ROS middleware, and MATLAB/Simulink integration. While both platforms are ideal for research and education, it was noted that they possess a steep learning curve due to their complexity. It was concluded that alternative platforms such as LibrePilot, Betaflight, and iNAV have limited utility in research environments.

When the studies examined within the scope of Section 4 are evaluated as a whole, it is evident that Digital Twin and SITL methodologies are increasingly maturing within the UAV ecosystem. Nevertheless, an integrated Digital Twin architecture that updates battery SoH estimation and dynamic energy consumption models in real-time, and incorporates an event-triggered re-simulation mechanism specific to spraying missions, remains an open research challenge in the current literature.

5. EVENT-DRIVEN DECISION SUPPORT AND FAULT TOLERANCE

In autonomous UAV systems, unexpected events—such as sudden drops in battery capacity, actuator failures, changes in weather conditions, or dynamic interruptions in the mission environment—necessitate the activation of real-time decision mechanisms.

This section provides a comparative analysis of semantic event processing approaches in Cyber-Physical Systems (CPS), event-triggered real-time route planning, and multi-UAV resilience systems.

5.1 Event-Driven Decision Making in Cyber-Physical Systems

Event-driven decision-making mechanisms in Cyber-Physical Systems are based on the principle of triggering actions in response to significant changes in system state, rather than continuous monitoring. This approach reduces the computational load and shortens the response time to critical situations.

Steindl et al. [23] proposed a technology-independent, semantic event processing module for explainable Cyber-Physical Systems. The proposed architecture connects rule-based, model-based, and complex event detection components via an event broker and adds context information to detected events through a semantic model. Two case studies conducted in the fields of smart buildings and smart grids validated the feasibility of the approach. A prominent contribution of the study is the semantic bridge established between event detection and explanation generation, rendering system decisions traceable and interpretable. However, the study is not directly applied to UAV systems or energy management.

For agricultural UAVs, this conceptual framework is especially relevant because semantically defined events—such as battery state of charge dropping below a critical threshold, unexpected wind impact, or tank depletion—could serve as the core triggers of an event-driven digital twin architecture.

5.2 Real-Time Route Replanning

UAV route planning in dynamic environments requires algorithms that can adapt to changing conditions during the mission, rather than merely following an initially calculated optimal trajectory.

ET-MAPIO [24], an event-triggered multi-modal adaptive pigeon-inspired optimization algorithm, addresses the real-time route planning problem for autonomous UAVs. The study overcomes issues such as falling into local optima and slow convergence through a multi-modal state update strategy and adaptive inertia weights. The developed event-triggering mechanism enables rapid and efficient route replanning in the presence of moving threats. The study focuses on military reconnaissance scenarios; energy constraints and battery status were not included in the route optimization criteria.

This gap is particularly noteworthy for agricultural spraying scenarios: an approach where real-time route replanning, triggered by events such as wind impact or payload depletion dynamics, is correlated with the energy budget is absent from the reviewed studies.

5.3 Multi-UAV Resilience Systems

Resilience in multi-UAV systems refers to the preservation of mission continuity against unexpected disruptions and requires the development of real-time recovery strategies.

Chen et al. [25] presented a resilience-oriented real-time decision-making framework for multi-UAV systems. A resilience metric combining mission completion rates and maintenance resource requirements was defined, and a joint optimization model encompassing component maintenance and task rescheduling was formulated. Simulation results showed that system resilience

could be increased from 0.82 to 0.95 in early-stage disruption scenarios. The limitation of the study is that tests were conducted on a limited number of UAVs and scenarios, and the integration of energy management into the decision mechanism remained superficial.

Qadir et al. [26] extensively addressed the role of UAV networks in disaster management by applying a multi-layered DT architecture. Their study examines how DT components facilitate deployment optimization, resource allocation, and mission handover through machine learning-based Decision Support Systems. While the interrelated nature of physical and virtual layers is comprehensively demonstrated for uncertain operational environments, the framework lacks in-depth integration of energy modeling and battery management.

Hall et al. [27] presented the DroNS-3 framework, which integrates the ArduPilot drone simulator with the NS-3 network simulator. This open-source library enables the validation of multi-UAV data collection path planning on both simulation and physical hardware, considering energy and communication constraints. The primary focus of DroNS-3 is network simulation, and its energy modeling and battery management functionality remains limited.

6. RESEARCH GAPS AND FUTURE DIRECTIONS

The systematic literature review presented in the preceding sections reveals four interconnected fundamental research gaps in the field of energy management and Digital Twin-based Decision Support Systems for Agricultural UAVs. These gaps are discussed in detail below, with proposed research directions for each. As conceptually synthesized in Figure 2, these deficiencies are not isolated problems but rather symptoms of a fragmented modeling approach: current literature tends to treat payload depletion, wind perturbations, and battery SoH as independent variables, whereas their operational coupling is what determines real-world mission success.

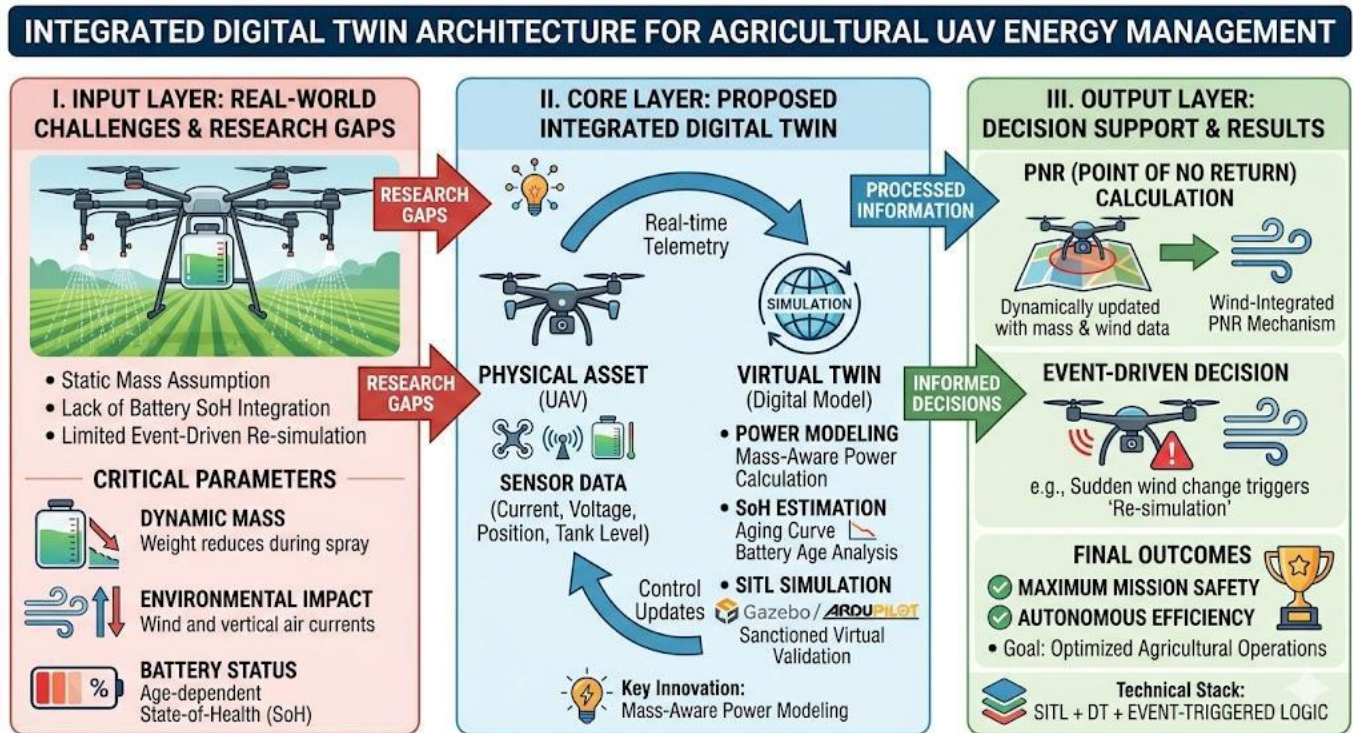


Figure 2. Proposed event-driven digital twin architecture for agricultural UAV energy management.

6.1 Integration of Payload Depletion Dynamics into the Energy Model

The power consumption models [9, 10, 11] and flight endurance estimation studies [7, 8] examined in Section 2 are built upon a common assumption: that the total mass remains constant throughout the mission. In agricultural spraying scenarios, however, this assumption does not reflect reality. As the chemical tank depletes during the mission, the platform mass continuously decreases; this reduction directly affects rotor thrust requirements and, consequently, power consumption. While Hwang et al. [9] experimentally demonstrated the impact of payload mass on endurance, the scenario where this impact changes dynamically during the mission was not addressed.

Addressing this gap requires the development of an adaptive power model that takes instantaneous tank fill levels as an input and updates energy consumption estimations in real-time. Such a model could provide more realistic endurance estimations specific to agricultural mission scenarios by correlating the mass reduction function—based on liquid flow rate and tank geometry—with multi-rotor power equations.

6.2 Wind Perturbation and PNR-Based Dynamic Decision Mechanism

The energy-aware CPP studies examined in Section 3 [13, 14] optimize mission planning under static environmental conditions. Li et al. [16] extensively demonstrated the effect of the wind field on spraying performance; however, correlating this effect with energy management and return decisions was not addressed. Furthermore, studies focused on return-to-home mechanisms [15,

17] do not model the specific energy threshold upon which the return decision is based or how this threshold should be dynamically updated mid-mission.

Although an industrial application approaching an energy-threshold-based return decision was presented by Yang [28] and Lei [29] within a patent scope, this approach lacks academic validation. It fails to account for battery SoH degradation, payload depletion dynamics, and agricultural spraying conditions, and it lacks Digital Twin integration. Consequently, a Digital Twin-assisted PNR-based decision mechanism that simultaneously accounts for wind impact, SoH, and instantaneous payload changes remains unaddressed in the academic literature.

6.3 Integration of Battery SoH and Real-Time Energy Estimation

Schacht-Rodriguez et al. [8] modeled the impact of battery aging on flight endurance, while Di Nisio et al. [6] validated LiPo discharge behavior under variable power loads. These two studies are complementary but have not been applied integratively in Agricultural UAV scenarios. Arsalan et al. [12] integrated federated learning and Digital Twins into energy management; however, this study also lacks battery characterization specific to agricultural platforms and has not been validated on physical hardware.

An integrated framework where battery SoH is predicted in real-time, combined with an instantaneous power consumption model, and directly fed into mission planning, stands out as an unaddressed approach for Agricultural UAVs. Especially in agricultural operation conditions where repeated charge-discharge cycles are concentrated during harvest seasons, reflecting SoH degradation in mission planning and PNR calculations is of critical importance for operational reliability.

6.4 Event-Driven Re-simulation Mechanism

Studies on Digital Twin-based UAV applications [18, 19, 22] focus on the use of simulation for pre-field planning and validation. Steindl et al. [23] established the conceptual framework for semantic event processing in the CPS context, and Qadir et al. [26] discussed the potential of Digital Twin-assisted decision-making in disaster management. However, none of these studies address the scenario where an event occurring during the mission—such as an unexpected drop in battery capacity or a sudden change in wind conditions—triggers an instantaneous re-simulation on the Digital Twin, with the simulation results being fed back into the real-time decision mechanism.

An event-driven re-simulation approach could enable the rapid execution of an anomaly detected mid-mission on the Digital Twin, allowing for the selection of the most appropriate recovery strategy among possible scenarios. No study integrating event-driven re-simulation with Agricultural UAV energy management was found in the reviewed literature.

7. CONCLUSION

This study has synthesized the current state of digital twin-based energy management for agricultural UAVs, revealing critical limitations in existing modeling frameworks. Our analysis demonstrates that without a payload depletion dynamics model, PNR calculations lack the necessary precision for autonomous spraying missions. Furthermore, without the integration of battery SoH and wind-integrated re-simulation mechanisms, Digital Twins remain limited to reactive monitoring rather than evolving into proactive, energy-aware safety systems.

The design and validation of an integrated Digital Twin architecture that unifies these four components—dynamic mass, wind impact, SoH, and event-driven re-simulation—represent the primary research agenda for the next generation of precision agriculture UAVs. Successfully bridging these gaps will transition UAV operations from fixed-threshold heuristics to dynamic autonomy, ensuring both mission efficiency and flight safety in complex agricultural environments.

The practical implication of these findings extends beyond academic modeling. As agricultural UAV fleets scale in commercial deployment, fixed-threshold safety heuristics will increasingly fail under the combined stress of battery aging, variable payloads, and unpredictable wind fields. The framework outlined in this review suggests that Digital Twin architectures capable of real-time SoH tracking, payload-aware power modeling, and event-triggered re-simulation are not merely a research aspiration but an operational necessity for next-generation precision agriculture systems.

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Ethical Statement

This study consists solely of a literature review conducted on publicly available academic publications and patents. As it does not involve human or animal participants, ethics committee approval is not required.

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Author Contributions

Literature review, conceptual framework development, writing, and final editing were carried out by S. Gümüştay. Supervision and academic mentorship were provided by Fatih Özyurt.

Data Availability Statement

No new data was generated in this study. All sources used in the analysis are publicly accessible through the relevant references.

Conflicts of Interest

The author declares no conflicts of interest related to this study.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the author utilized advanced language models and artificial intelligence tools to assist in the technical translation from the source language to English and to enhance the academic linguistic quality of the manuscript. Following the use of these tools, the content was thoroughly reviewed, edited, and verified by the author to ensure technical precision. The authors take full responsibility for the scientific integrity and accuracy of the final manuscript.

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