Empirical Analysis of Battery Management and Load Optimization for Electrical UAV Energy Efficiency

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Abstract:

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, are increasingly utilized worldwide for applications such as surveillance, inspection, mapping, and logistics. Functioning as a subsystem of electric vehicles (EVs), UAVs rely on high-energy-density battery technology to enable efficient autonomous operation. Given their limited onboard battery capacity, optimizing energy consumption is crucial to balancing mission objectives with recharging needs during extended flights. This study explores automated tour optimization strategies for energy-constrained UAVs by developing a predictive model that estimates energy consumption in multi-rotor drones while accounting for real-world conditions and external environmental factors. A provably efficient approximation method is formulated to optimize flight planning while ensuring real-time adaptability. The proposed approach is integrated into a drone management system that enables continuous flight path monitoring and dynamic re-computation. Extensive real-world experiments validate the practicality and effectiveness of this framework in enhancing UAV energy efficiency and operational reliability, while also contributing to advancements in EV battery management and power optimization.

Keywords:

1. Introduction:

The increasing reliance on unmanned aerial vehicles (UAVs) for applications such as environmental monitoring, search and rescue, precision agriculture, and logistics necessitates robust energy management strategies. UAVs offer significant advantages, including energy efficiency, agile navigation, rapid deployment, and cost-effectiveness, making them integral to smart city ecosystems. However, a major limitation of current UAV technology is restricted flight endurance due to battery constraints, exacerbated by environmental factors such as wind resistance. To enhance long-haul UAV operations, a comprehensive energy management framework is essential.

As the demand for electric mobility grows, high-voltage, high-efficiency, and long-lifespan battery systems are critical. Battery balancing technology plays a pivotal role in optimizing performance, with balancing schemes classified as passive or active, each offering trade-offs in efficiency, complexity, and cost. The choice of balancing method must align with specific operational requirements. Given that agricultural UAVs are projected to dominate approximately 80% of the drone market, overcoming their limited flight duration is a pressing challenge.

To address this, high-capacity rechargeable battery systems—such as lead–acid, nickel–cadmium (Ni-Cd), nickel–metal hydride (Ni-MH), and lithium-ion (Li-ion) batteries—are deployed in agricultural UAVs. Among these, Li-ion batteries exhibit superior power density, high energy efficiency, and a low self-discharge rate, making them ideal for extended flight durations. However, large-capacity UAV batteries are typically composed of multiple cells in series/parallel configurations, leading to potential voltage imbalances due to electrochemical side reactions, impedance variations, and differential charge/discharge cycles. Additionally, overcharging can accelerate material degradation, increasing internal pressure and reducing battery lifespan.

This paper presents a battery cell balancing algorithm integrated with a three-stage alarm system within a Battery Management System (BMS) to enhance UAV flight endurance. The proposed approach optimizes energy efficiency, automation, and sustainability by dynamically adjusting power distribution based on varying load conditions and environmental factors. By incorporating real-time monitoring and predictive energy management, the system mitigates cell imbalance, ensuring prolonged operational duration and improved battery longevity under diverse flight scenarios.

2. System Model and Experimental Setup:

This study presents a battery endurance estimator for UAVs to optimize flight efficiency and energy management. A 10 kg payload agricultural drone with a 22,000 mAh battery is developed, integrating key subsystems for stable flight, precise navigation, and mission execution, with detailed system architecture analysis.

Figure 1. The block diagram illustrates the different stages of the designed bidirectional EV charger.

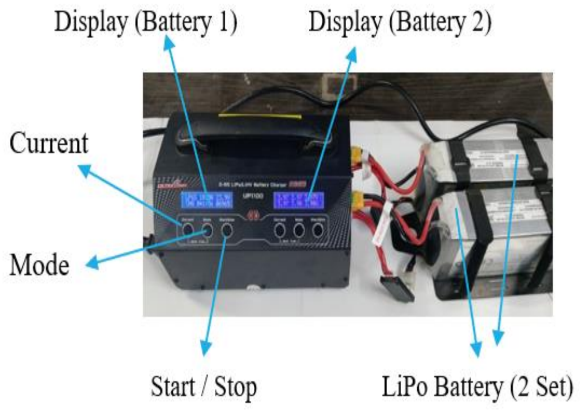
2.1 Unmanned Aerial Vehicles (UAVs):

The hexacopter drone system comprises multiple integrated subsystems, including the airframe, propellers, GPS module, brushless DC (BLDC) motors, and payload. Figure 1 provides a detailed illustration of these components. The BLDC motors and propellers work in coordination to generate lift and maintain controlled flight, regulated by the flight controller. The airframe and arms, constructed from lightweight yet durable carbon fiber, serve as the structural foundation, linking the motors to the main body while ensuring mechanical stability. Additionally, the GPS module is interfaced with the transmitter to facilitate precise positioning, navigation, and real-time location tracking for autonomous or semi-autonomous operations.

2.2 UAV Flight Controller and Communication System:

The primary control module of the UAV shown in Figure 2 comprises the flight controller (FC), power module, and receiver, which collectively govern the drone’s operations. The Jiyi K++ V2 Flight Controller is specifically utilized due to its advanced capabilities in managing heavy-lift drones, ensuring precise control based on real-time commands received from the transmitter. The flight controller serves as the central processing unit, interfacing with all onboard components to execute flight maneuvers and maintain stability.

2.3 Eclectic Battery charging and Power Distribution subsystem:



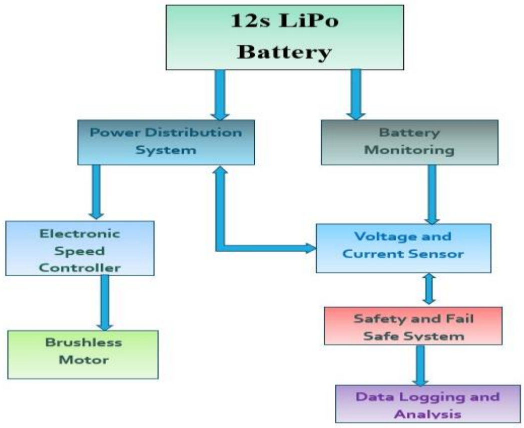


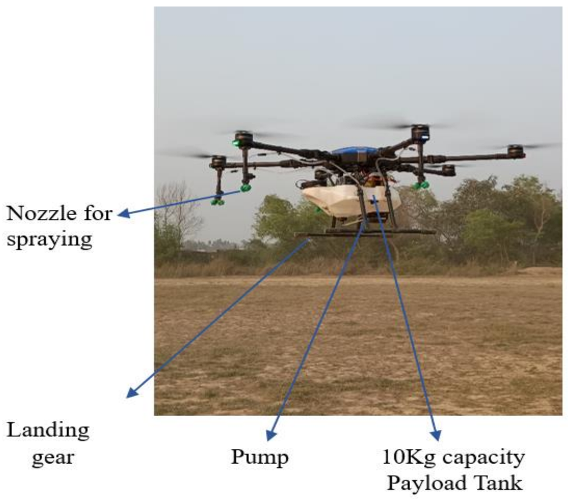
Figure 2. Power transfer in bidirectional EV charging

Figure 5 illustrates the UAV battery charging module, which features a dual-unit charging system capable of simultaneously charging two battery packs. Each unit supports a maximum charging current of up to 10A and delivers an output power of up to 1100W, ensuring efficient and rapid recharging of UAV batteries to minimize operational downtime. The system is designed with smart charging capabilities, incorporating voltage and current regulation mechanisms to enhance battery longevity and optimize charging efficiency.

Figure 6 presents the 12S LiPo battery pack, which serves as the primary energy source for the UAV. The power distribution system (PDS) is integrated to distribute electrical energy to key components, including the ESCs and BLDC motors, ensuring stable and efficient power delivery during flight. Additionally, a battery monitoring system (BMS) is incorporated, featuring voltage and current sensors, a safety alarm system, and a real-time data acquisition module. This system continuously monitors battery performance and transmits critical data to both the flight controller and power distribution system, facilitating adaptive power management for smooth operation and enhanced flight stability.

Furthermore, the BMS data is analyzed for algorithm development, enabling predictive maintenance, energy optimization, and improved flight efficiency. By leveraging real-time monitoring and data-driven decision-making, the system enhances UAV reliability, prevents power failures, and contributes to the overall sustainability of the drone's energy management framework.

2.4 Payload subsystem and Flight Mission:



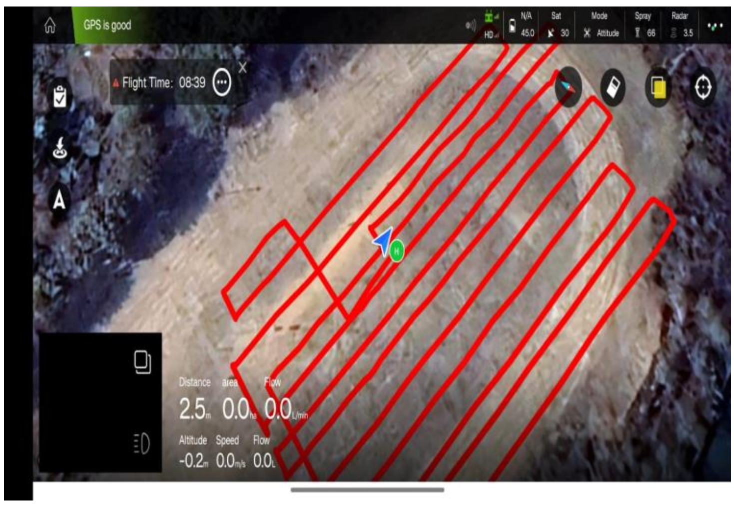


Figure 2. Power transfer in bidirectional EV charging during V2G and G2V modes

Figure 5 illustrates the UAV hovering at an altitude of approximately 1.5 meters above the ground while carrying a 10 kg payload. The payload subsystem is designed for precision agricultural spraying and consists of an integrated tank, spray nozzles, and a pump, all of which are regulated via the transmitter to achieve a controlled spray rate. To enhance coverage efficiency, the system incorporates four strategically positioned spray nozzles, mounted on the drone's arms, ensuring uniform distribution of liquid over the designated field area.

Figure 6 presents the coverage mapping of the drone, demonstrating its capability to effectively spray an area of approximately 2 acres during a single flight mission lasting 8.39 minutes (519 seconds) at full payload capacity. The experimental testing and data collection were conducted at the Government Polytechnic Deoria UP, serving as a controlled environment to validate the UAV’s operational efficiency and precision in agricultural applications.

3. Experimentation Results and Analysis:

The UAV system integrates developer kits and mission planner software, enabling real-time extraction of sensor data and precise flight path programming. The onboard barometer and GPS modules facilitate accurate three-dimensional motion tracking, ensuring stable navigation and altitude control.

Figure 7 presents key flight parameters, including ground speed, positional coordinates, and altitude, obtained through a combination of GPS and Inertial Measurement Unit (IMU) sensors, with altitude measurements further refined using the barometer and GPS. The figure also illustrates the total flight duration of the UAV under no-load conditions, correlating flight time with voltage drop, as detailed in Table 1, which provides a time-dependent voltage profile.

Table 1.

Time (Min)	Voltage(V)	Voltage Drop (%)	Time (Min)	Voltage (V)	Voltage Drop (%)
1:00	46.3	100.00	13:00	42.1	59.22
2:00	45.8	95.15	14:00	42.0	58.25
3:00	45.4	91.26	15:00	41.8	56.31
4:00	45.0	87.38	16:00	41.8	56.31
5:00	44.4	81.55	17:00	41.7	55.34
6:00	44.0	77.67	18:00	41.5	53.40
7:00	43.7	74.76	19:00	41.2	50.49
8:00	43.3	70.87	20:00	40.7	45.63
9:00	43.0	67.96	21:00	40.0	38.83
10:00	42.7	65.05	22:00	39.6	34.95
11:00	42.5	63.11	22.47	39.2	31.07
12:00	42.3	61.17			

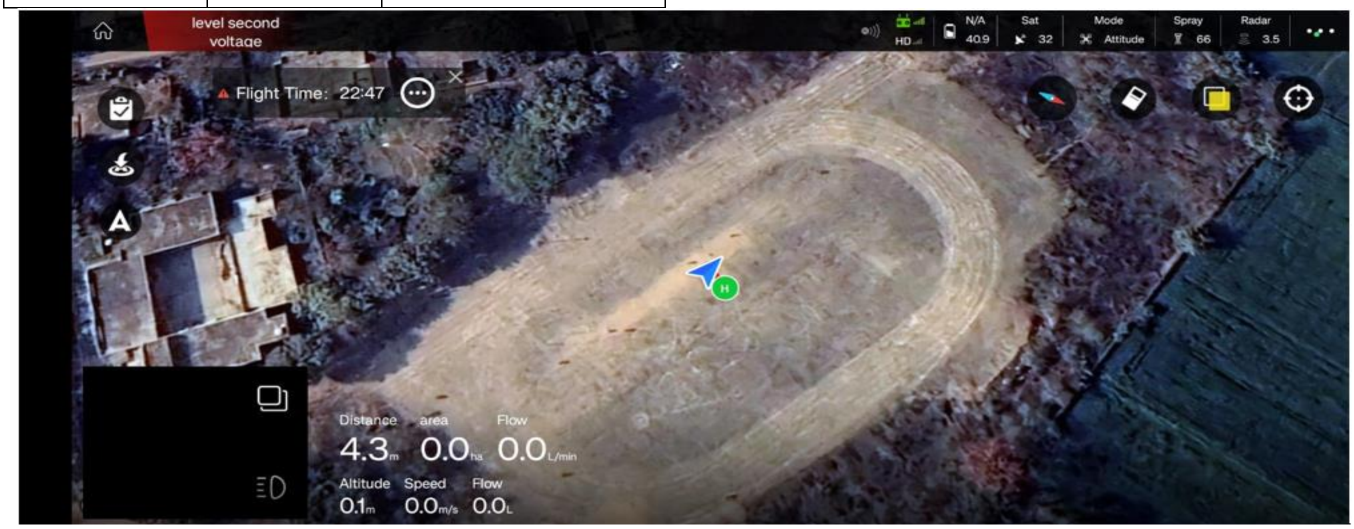


Figure 7.

Additionally, Figure 7 incorporates a satellite map overlay, validating the flight trajectory and data acquisition process. This comprehensive dataset plays a crucial role in battery management system (BMS) optimization, facilitating performance analysis and efficiency improvements for enhanced UAV energy utilization.

Figure 8 presents the graphical analysis of battery voltage depletion over UAV flight time, emphasizing critical thresholds for power management and flight safety. To optimize the Battery Management System (BMS) and enhance operational reliability, a three-tier alert system is integrated to provide real-time notifications via the transmitter at predefined voltage levels.

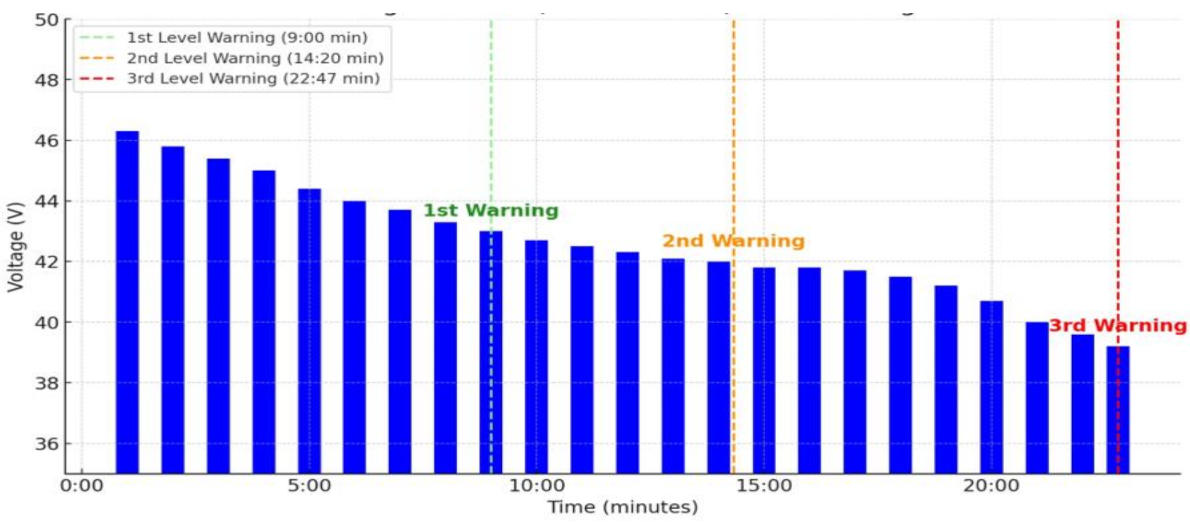


Figure 3. The figure displays three-phase voltage graphs during charging mode.

The first alert is activated at approximately 43V, indicating 35% battery consumption, serving as an early warning to the operator. The second alert is triggered at 42V, corresponding to 45% energy depletion, with cumulative flight durations recorded at approximately 9 and 14 minutes, respectively.

To ensure safe Return-to-Home (RTH) and controlled landing, the third alert is initiated at 39V, marking 30% remaining battery capacity. This precautionary measure is essential, as UAVs experience high initial power demand, depleting nearly 25%-28% of total battery capacity during takeoff due to peak energy requirements. The proposed multi-level alert system ensures efficient power regulation, enhances UAV flight autonomy, and prevents critical power failures, thereby improving overall endurance and energy optimization.

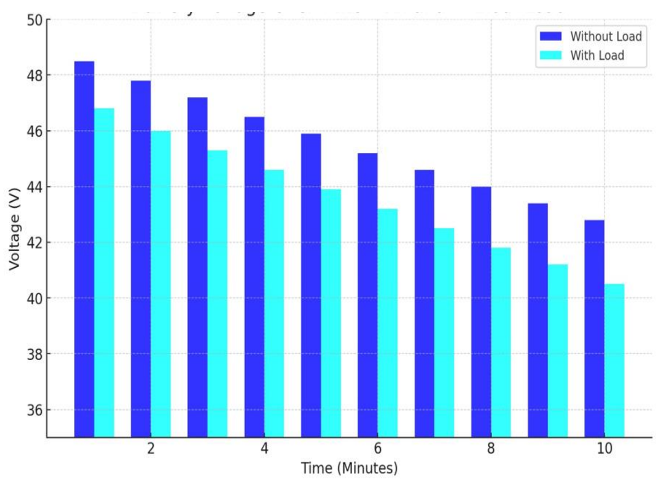


Figure 9. DC voltage before the buck converter.

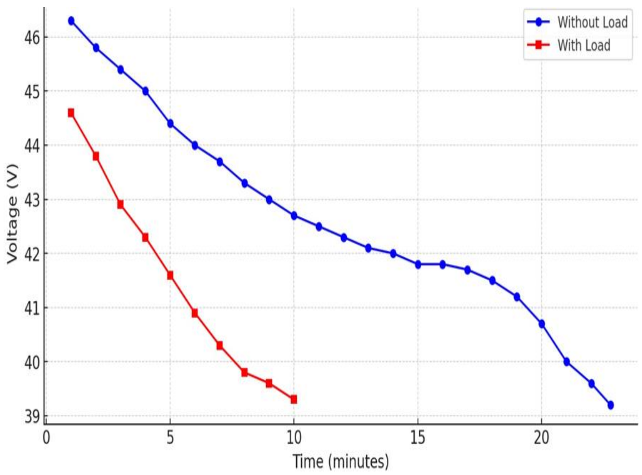


Figure 10. DC voltage of the battery after the boost converter.

A comprehensive full-load flight experiment was conducted with active spraying operations to evaluate the impact of payload on battery performance. The recorded data was analyzed, and the corresponding bar graph in Figure 9 compares UAV performance under full-load conditions (10 kg payload) versus no-load conditions, illustrating variations in flight time and voltage depletion.

To further understand real-time load variations and their effect on flight duration, an in-depth analysis was performed, with findings visualized in Figure 10. The results clearly indicate that effective load management can enhance overall system efficiency by approximately 20–22% compared to conventional flight operations.

The experimental data was utilized for the development of an optimized battery management algorithm, aiming to improve battery efficiency, extend flight duration, and enhance UAV operational reliability. This framework contributes to intelligent power distribution strategies, ensuring optimal energy utilization for sustained UAV performance.

4. Conclusion:

The experimental analysis demonstrates that effective battery management and load optimization significantly enhance UAV energy efficiency and operational reliability. The proposed multi-level alert system ensures precise power regulation, preventing critical failures and improving flight autonomy. Full-load flight tests reveal that optimized payload distribution increases system efficiency by 20–22%, directly impacting battery longevity and flight duration. The findings contribute to the development of an intelligent battery management algorithm, enabling real-time energy optimization and enhancing UAV performance for extended missions.

5. References

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