Late Breaking Results: Thermal-Aware Drone Battery Management

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ABSTRACT

Users have reported that their drones unexpectedly shutoff even when they show more than 10% remaining battery capacity. We discovered that the causes of these unexpected shutoffs to be significant thermal degradation of a cell caused by thermal coupling between the drones and their battery cells. This causes a large voltage drop for the cell affected by the drone heat dissipation, which leads to low supply voltage and unexpected shutoffs. This paper describes the design and implementation of a thermal and battery-aware power management framework designed specifically for drones. Our framework provides an accurate state-of-charge and state-of-power estimation for individual battery cells by accounting for their different thermal degradation. We have implemented our framework on commodity drones without additional hardware or system modification. We have evaluated its effectiveness using three different batteries demonstrating our framework generates accurate state-of-charge and prevents unexpected shutoffs.

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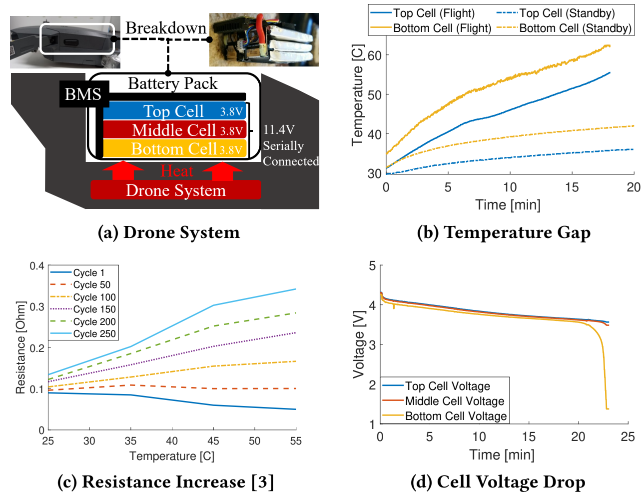
1 INTRODUCTION

Drone users are reported to have experienced unexpected shutoffs during flights [1], even when the drones are shown to have about 10% remaining battery state-of-charge (SoC) — the percentage of remaining capacity relative to the total usable capacity when the battery is fully charged; such battery related issues cause more than 200 incidents every year [2]. Our case study demonstrates that such an unexpected shutoff occurs at as low as 64 battery cycles, i.e., within battery warranty period of 200 cycles, and causes crashes at 7-9% SoC. Our experiments also show that heat dissipation from drone causes a large thermal imbalance across battery cells, up to 6 C during standby and 10 C during flight. Such temperature imbalance causes an unbalanced battery cell aging, which leads to SoC overestimation and unexpected shutoffs.

To this end, we design a drone battery management framework specifically designed for commodity drones without requiring any additional hardware or OS modifications. Our framework predicts the dynamic cell-level temperature, captures the cell-level battery internal resistances, and estimate SoC in real-time. Our framework (i) profiles battery cell parameters offline, on the ground, by generating novel discharging pulses, and, (ii) estimates real-time cell SoC during the flight by combining profiled and runtime cell parameters. During the offline profiling, our framework discharges the battery with intermittent discharging pulses, and then determines the cell resistances to compensate for the cell-level capacity.During the flight, our framework further calibrates the profiled cell parameters, and estimates cell SoC by combining both cell parameters and runtime measurements. We have deployed and evaluated our framework on a commodity drone demonstrating that our framework prevents sudden SoC drop and unexpected shutoffs capturing cell-level thermal degradation.



(a) Drone System (b) Temperature Gap (c) Resistance Increase [3] (d) Cell Voltage Drop

Figure 1: Drone (a) heat dissipation causes different (b) temperatures, (c) resistance, and (d) voltage drop across cells.

2 CAUSES OF UNEXPECTED DRONE SHUTOFFS

To understand the battery behaviors, we analyzed two commodity drones: (i) Mavic Pro with three 3.8V 3830mAh serial cells, (ii) Mavic Air 2 with three serial 3.8V 3500mAh serial cells. Fig. 1a illustrates the common architecture for these drones where battery cells are tightly packed with drone body for compact design. Due to this sharing of the rather small physical space, battery cell temperature is significantly affected by the heat dissipation of the drone. we highlight three key observations during the flight of Mavic Pro. The cell temperature of bottom cell, i.e., closer to the drone, is 5 C higher than the top cell during standby, 10 C higher during flight, leading to a significant temperature imbalance across the battery cells (Fig. 1b). Higher cell temperature accelerates the cell thermal degradation resulting in increased cell resistance (Fig. 1c). The battery cells with

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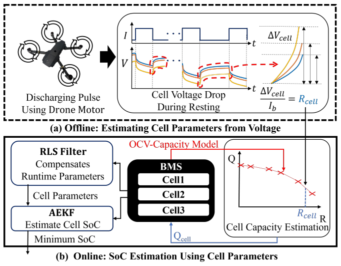

Figure 2: Thermal-Aware Drone Battery Management Overview.

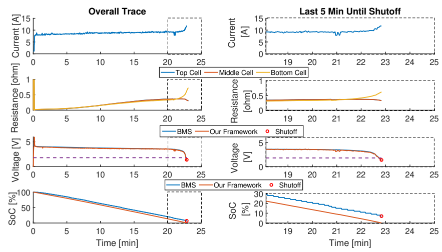

Figure 3: Current, resistance, voltage, SoC with and without our framework.

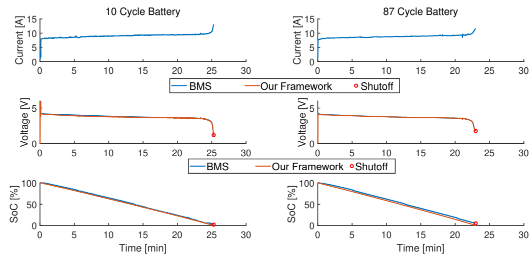

Figure 4: Drone battery management on batteries with different cycles (10 vs. 87 cycles)

significant temperature imbalance show different voltage drops, i.e., the cell with high temperature shows sudden voltage drop (Fig. 1d).

These observations led to our conjecture that *the bottom cell is exposed to the drone heat dissipation and experiences severe thermal degradation, thus causing sudden voltage drop and unexpected shutoffs.* Assuming that this conjecture holds, we measured the capacity of the individual cell by integrating the discharge current drained, i.e., $Q_{bat} = \int I_{bat} \cdot dt$. The bottom cell showed a capacity of 87% of the nominal capacity while the top cell's capacity was 95%. The drone battery management system (BMS) may overestimate the SoC by 8% due to the imbalance in cell thermal degradation.

To corroborate this conjecture, we also conducted case studies to spot unexpected shutoffs and analyze the battery performance in a realistic setup. We operate a fully-charged Mavic Pro by hovering until it shut off while tracking the voltage, discharge current, and SoC measured by BMS. When the battery voltage drops, the discharge current soars rapidly to supply an equal amount of power, which leads to over-discharge of the cell and unexpected shutoffs. Unexpected shutoff occurs at 8% implying that the BMS falls short in capturing the cell-level different capacity fading and overestimates SoC. Accumulating the current, the capacity withdrawn from the battery was 3379mAh, 88% of nominal capacity of 3830mAh.

3 FIXES OF UNEXPECTED DRONE SHUTOFFS

As drones have little control over their battery's cell temperature, our focus is to capture the cell thermal degradation and estimate an accurate cell-level SoC to prevent unexpected shutoffs. As shown in Fig. 2, our framework (i) profiles battery cell parameters in offline, on the ground, by generating novel discharging pulses, and, (ii) estimates real-time cell SoC during the flight by combining profiled and measured cell parameters using both recursive least square (RLS) filter and adaptive extended Kalman filter (AEKF). During offline profiling in Fig. 2a (dotted line), our framework discharges the battery with intermittent discharging pulses with, the rest periods in between, and then determines the cell resistance, R_{cell} at each SoC level from the voltage traces during the rest periods.

During online flight in Fig. 2b (solid line), our framework translates these cell-level resistances to cell-level capacity by constructing a capacity estimation model that maps cell resistance to capacity based on the OCV-capacity characteristics. Finally, our framework (i) further calibrates the profiled cell resistance with runtime measurements using an RLS filter, and (ii) estimates cell SoC by combining calibrated cell parameters and accumulated runtime discharge current, i.e., Coulomb counting, via AEKF. Note that our framework implements discharging pulses and SoC estimation by using the commodity drone's BMS driver and SDK interfaces without requiring additional hardware or system modifications.

4 EXPERIMENTAL RESULTS

We have implemented our framework as a user-level application using DJI Mobile SDK that automatically starts when the drone is turned on. We have evaluated our framework on a Mavic Pro with three batteries with 10, 64, and 87 dis/charging cycles.

Preventing Unexpected Shutoffs. In Fig. 3, we repeat the experiment shown in Fig. 1b, i.e., hovering the drone in a room temperature, with and without our framework during a full discharge cycle. At 22 min, the cell resistance increases rapidly for the bottom cell that has been affected by the drone heat dissipation. Without our framework, however, drone BMS overestimates the cell capacity and SoC without awareness of the cell-level thermal degradation. The peak current at 23 min causes an excessive voltage drop across the battery resistance, reducing the battery voltage to below the cutoff level; this causes the drone to shut off when the battery has an SoC of 8%. Our framework adaptively captures the cell capacity fading based on the increasing cell-level resistance, thus mitigating the SoC overestimation and sudden SoC drops. As a result, the drone shuts off when the battery SoC reduces steadily to 0%.

Experiments with Different Batteries. Finally, we compare our framework on the drone powered by two batteries of different cycles (i.e., at 10 and 87 cycles, respectively). Fig. 4 shows magnified advantages of our framework with aged batteries - the drone unexpectedly shut off at 5 % SoC for the aged battery compared to 1% for the new battery without our framework. Our framework estimates a SoC that steadily reduces to 0% for both batteries.

5 CONCLUSION

We present a thermal imbalance-aware battery management framework for drones to mitigate unexpected shutoffs caused by the different thermal coupling between drone and battery cells. We have implemented and evaluated our framework on commodity drones, demonstrating effectiveness in preventing unexpected shutoffs and generating an accurate SoC estimation.

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