Multirotor Unmanned Aerial Vehicle Long-Term Autonomous Mission Planning Under Battery Degradation

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Background

- Agricultural UAVs like the **DJI AGRAS T50** are used for large-scale crop monitoring
- Persistent monitoring requires: thousands of sorties, balancing field coverage with reactive response to **pest outbreaks**, autonomously managing its **energy budget**, **charging**, and **mission priorities**
- Lithium cells suffer irreversible **capacity fade and impedance growth** through cycling and calendar aging, reducing range and coverage
- Most planners treat battery capacity as fixed
- **Dual Process Theory (DPT)** from cognitive psychology separates fast, intuitive responses from slow, deliberative planning

Research Question and Objectives

- Can a battery degradation model, integrated into a **Dual Process Theory multi-layer decision making (MLDM)**, improve autonomous persistent field monitoring using MUAV?
- Develop a **semi-empirical**, **per-cycle** battery degradation model and embed it in a **DPT MLDM**
- Evaluate via **full-factorial simulation** over 180-day missions, measuring pest control, response time, crop damage, and coverage

DPT MLDM

- Four layer architecture inspired by Dual Process Theory (DPT), balancing fast reactive and slow deliberative control
- **System 1 (safety)**: monitors SOC; triggers return-to-home near the reserve floor
- **System 2 (reactive)**: responds to pest outbreaks during flight
- **System 3 (exploration)**: covers least-recently-visited field regions
- **System 4 (exploitation)**: sizes hotspot sorties, scaled to **battery capacity**
- Planning occurs **at the charging station**; conflict monitoring chooses between exploration vs. exploitation

DPT MLDM (Continued)

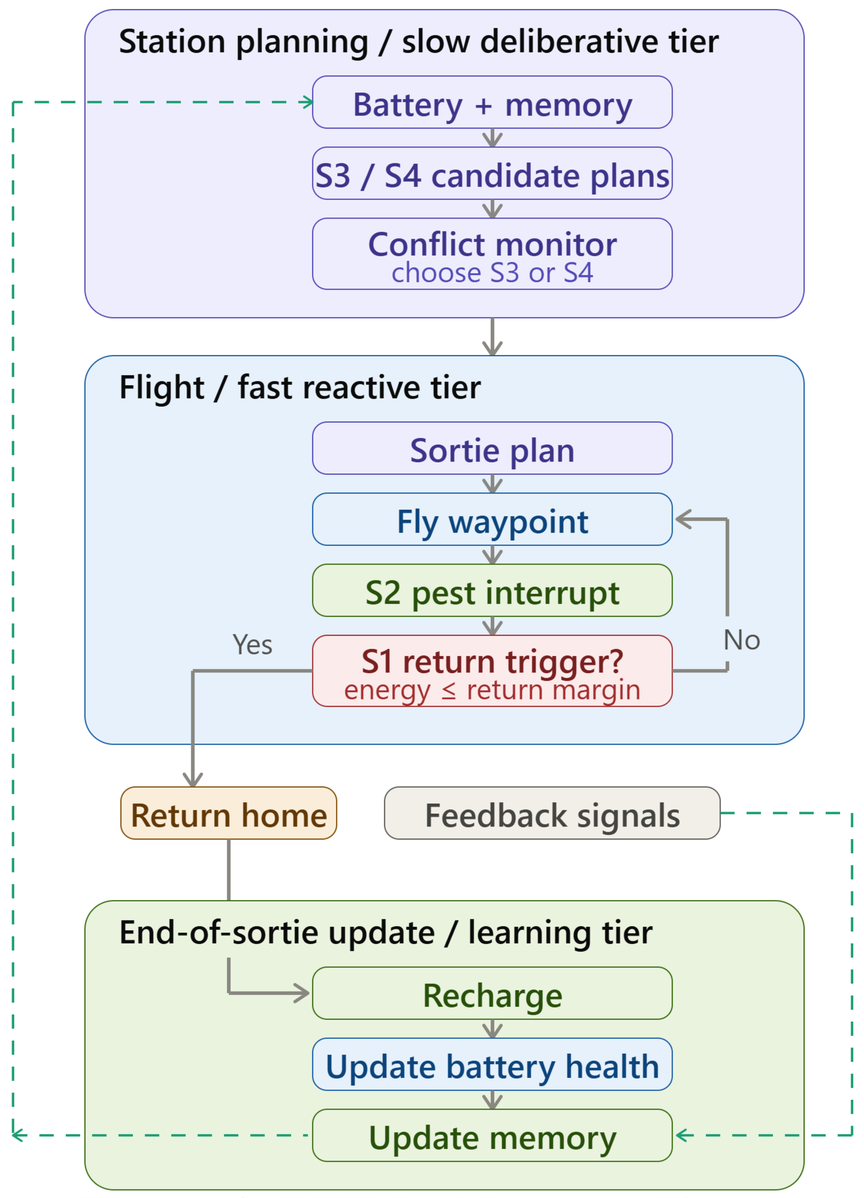

Figure 1: DPT Architecture Flowchart

Battery Degradation Model

- **Capacity fade** is modeled with a **semi-empirical**, **per-cycle** incremental formulation, computed once per sortie [3,4]
- Capacity lost per sortie from active use, combining **depth of discharge**, **C-rate**, **temperature**, and **SOC window** into one multiplicative damage law [3,4]

$$\Delta Q_{cyc} = k_{cyc} DOD^{\alpha} \left(\frac{C_{eff}}{C_{ref}}\right)^{\alpha_C} \phi_{eff} e^{\beta(SOC_{max}-0.5)}$$

- **Calendar fade**: capacity lost while the pack rests, following **square-root-of-time SEI growth** at the anode surface [4]
- Accelerated by **higher temperature** and storage charge; small over the mission but keeps the model accurate during long rests

$$\Delta Q_{cal} = k_{cal}\sqrt{\frac{t_{rest}}{t_{ref}}}\,\phi_{rest}\left[1+\gamma_{SOC}\left(\overline{SOC}-0.5\right)\right]$$

- Both aging modes become **interpretable scalars**
- An **equivalent-circuit + lumped-thermal model** provides voltage, SOC, and temperature to the aging law [2,5,6]
- Degradation feeds back to the DPT architecture as **SOH and usable capacity**

Battery Degradation Model (Continued)

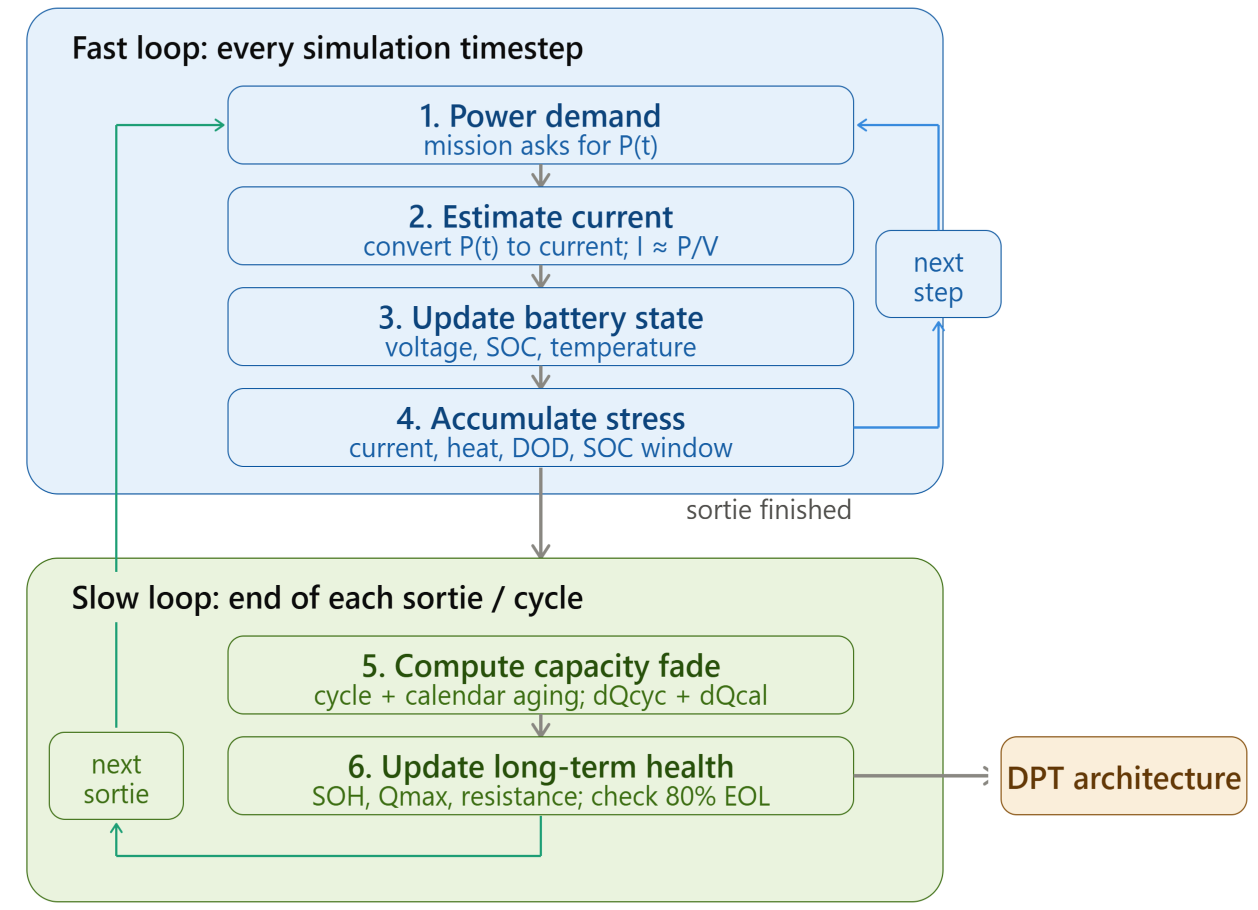

Figure 2: Battery Model Flowchart

Simulation Environment

- **4.4 km × 4.4 km** field, sized for roughly **one full sweep per day** on a fresh battery
- UAV: **10 m/s**, 10 m altitude, **25 m detection radius**, 50 m sweep spacing
- **180-day** continuous missions; new sortie launches as soon as charging completes
- Hidden **pest susceptibility map** (five hotspots, three cold zones) must be learned through experience
- Infestations appear **one per day** and progress through **three stages**: early, established (propagates), severe (2× cost)
- **48 configurations**: 2 chemistries × 3 SOC windows × 2 charge rates × 4 decision frameworks

Preliminary Results

- **Wider SOC windows** degrade faster: 100% vs 80% raises per-cycle damage **~20% (NMC)**, **~170% (LiPo)**
- **Fast charging (3C)** boosts throughput but accelerates degradation, lowering final SOH
- **DPT-Aware** expected to outperform DPT-Unaware on pest control and crop damage as the battery ages
- Both **DPT agents** expected to beat **lawnmower baselines** via reactive response and hotspot exploitation
- Conflict monitor expected to favor **exploration**, with periodic **exploitation bursts**

Conclusion

- Developed a **semi-empirical, per-cycle degradation model** capturing cycling and calendar fade, C-rate, temperature, and SOC stress
- Integrated it into a **DPT MLDM**, so battery health directly informs return-to-home and sortie planning
- Expect wider **SOC windows** and **fast charging** to trade mission throughput against battery life
- Expect **degradation-aware** agents to sustain coverage longer as capacity fades

UAV Hardware Validation

- Built a **Holybro quadrotor** with an **HRB 4S LiPo** (5000 mAh, 14.8 V, 50C) for real world data
- Logs realistic **power**, **current**, and **voltage profiles** while flying **simulation-analogous** routes
- Data will **validate the degradation model** and calibrate **LiPo** parameters

Figure 3: Holybro Drone Setup

References

[1] Cooper, N., et al. "Physics-Based Prediction of Remaining Useful Life of Lithium-Ion Batteries in Fuel Cell–Battery Hybrid Aircraft Using an Open-Source Modelica Framework." Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE), 2025, Paper IMECE2025-168114.

[2] Tran, Manh-Kien, et al. "A Comprehensive Equivalent Circuit Model for Lithium-Ion Batteries, Incorporating the Effects of State of Health, State of Charge, and Temperature on Model Parameters." Journal of Energy Storage, vol. 43, 2021, p. 103252, https://doi.org/10.1016/j.est.2021.103252.

[3] Saxena, Saurabh, et al. "Cycle Life Testing and Modeling of Graphite/$LiCoO_2$ Cells Under Different State of Charge Ranges." Journal of Power Sources, vol. 327, 2016, pp. 394–400, https://doi.org/10.1016/j.jpowsour.2016.07.057.

[4] Jin, Xiaofeng, et al. "Physically-Based Reduced-Order Capacity Loss Model for Graphite Anodes in Li-Ion Battery Cells." Journal of Power Sources, vol. 342, 2017, pp. 750–761, https://doi.org/10.1016/j.jpowsour.2016.12.077.

[5] Bernardi, D., et al. "A General Energy Balance for Battery Systems." Journal of the Electrochemical Society, vol. 132, no. 1, 1985, pp. 5–12, https://doi.org/10.1149/1.2113792.

[6] Allafi, Walid, et al. "A Lumped Thermal Model of Lithium-Ion Battery Cells Considering Radiative Heat Transfer." Applied Thermal Engineering, vol. 143, 2018, pp. 472–481, https://doi.org/10.1016/j.applthermaleng.2018.07.105.

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UNDERGRAD RESEARCH

This work is supported by the University of South Carolina's Molinaroli College of Engineering and Computing McNair Research Fellowship

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