
Progress Towards Digital Twin Integration for Online Battery Health Estimation in the SWIFT-UAV Platform

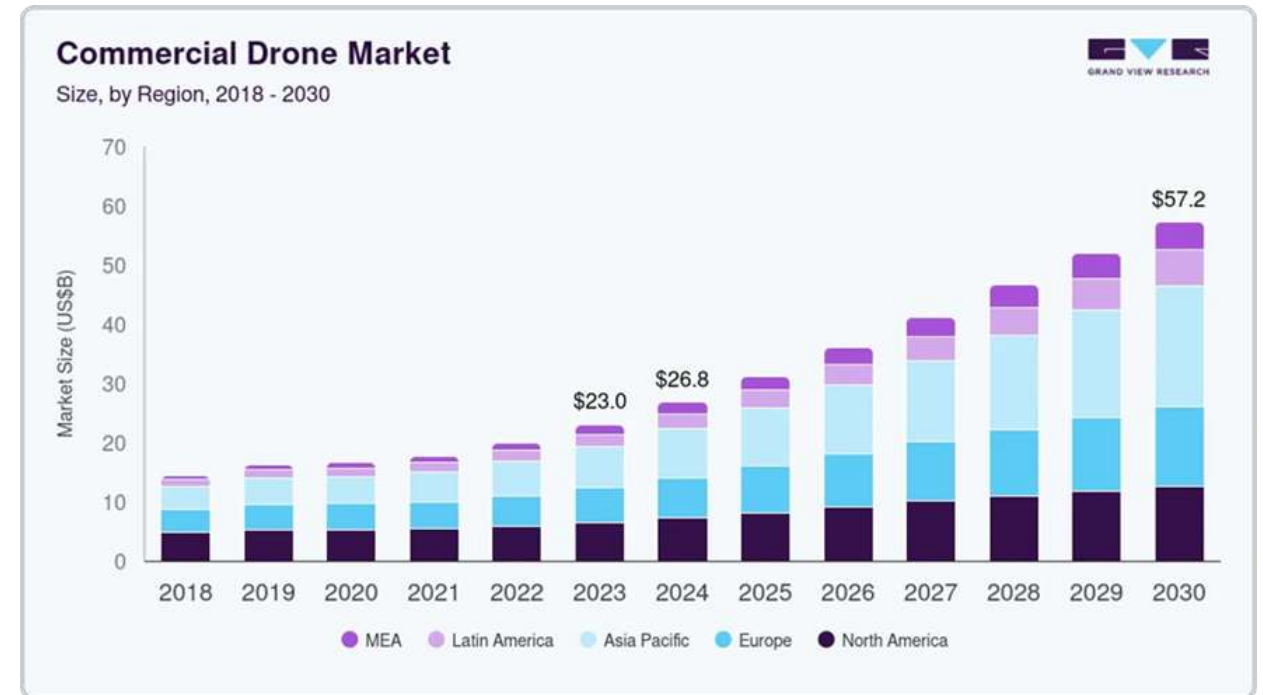
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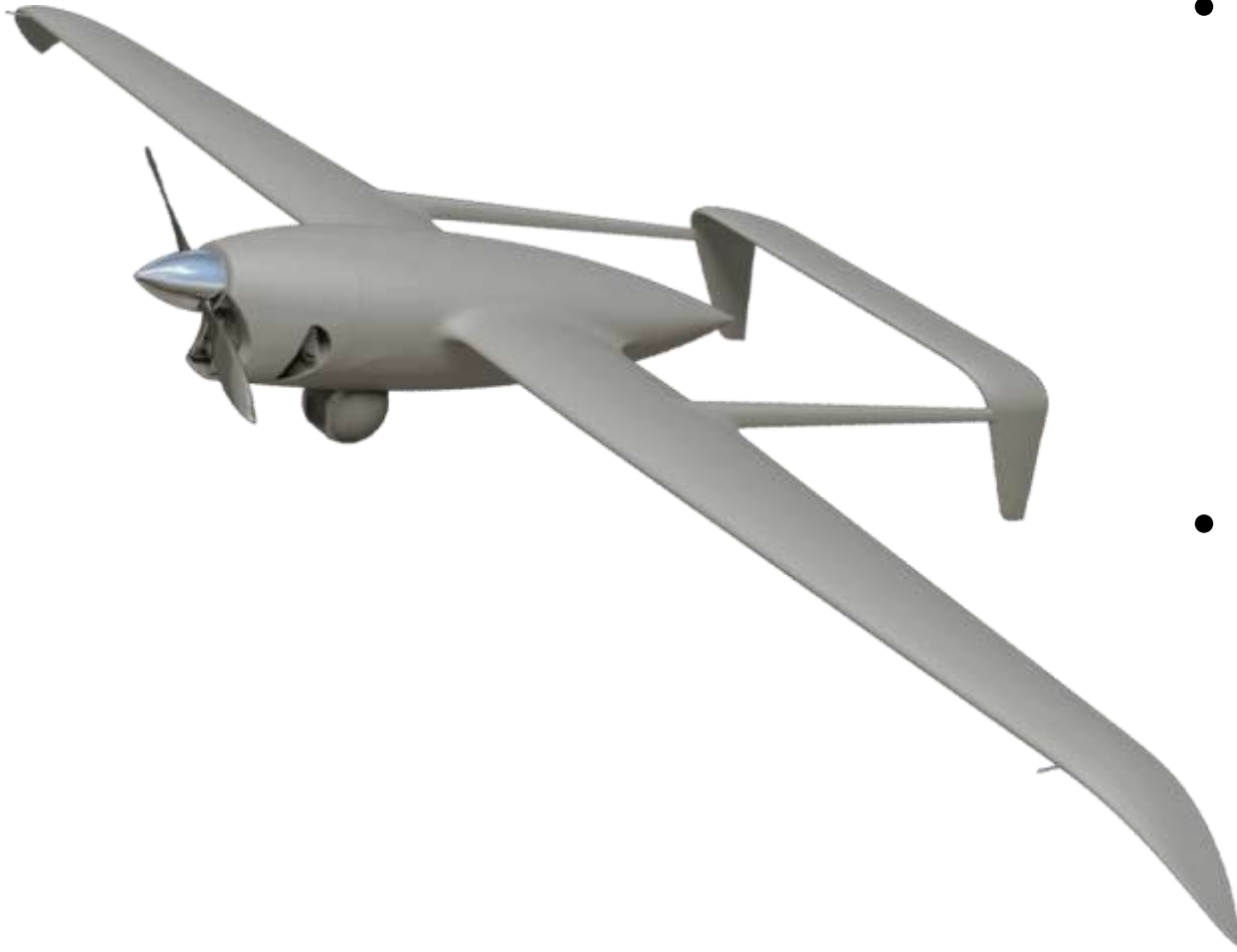
University of South Carolina

Background

- Unmanned Aerial Vehicles can be used to **complete complex mission** in various environments.
- The rapid growth of capability and demand has driven **significant growth** in the UAV market and accelerated adoption **across both civilian and defense sectors.**



Limits in UAV Performance



- Many UAV platforms are **closed-source**, which restricts customization and limits user control over system modifications.
- Commercial UAV systems are often **very expensive**, making them less accessible for research, development, and specialized applications.

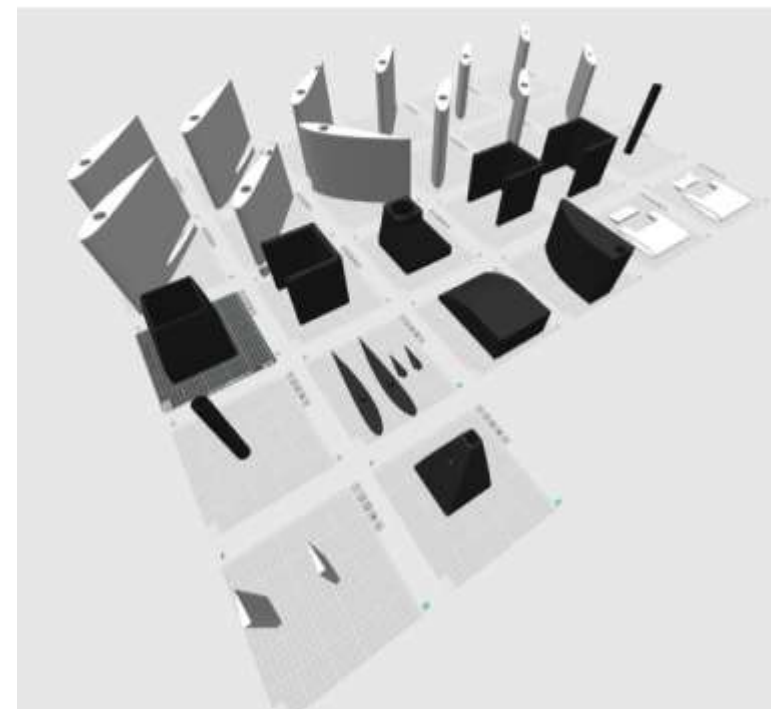
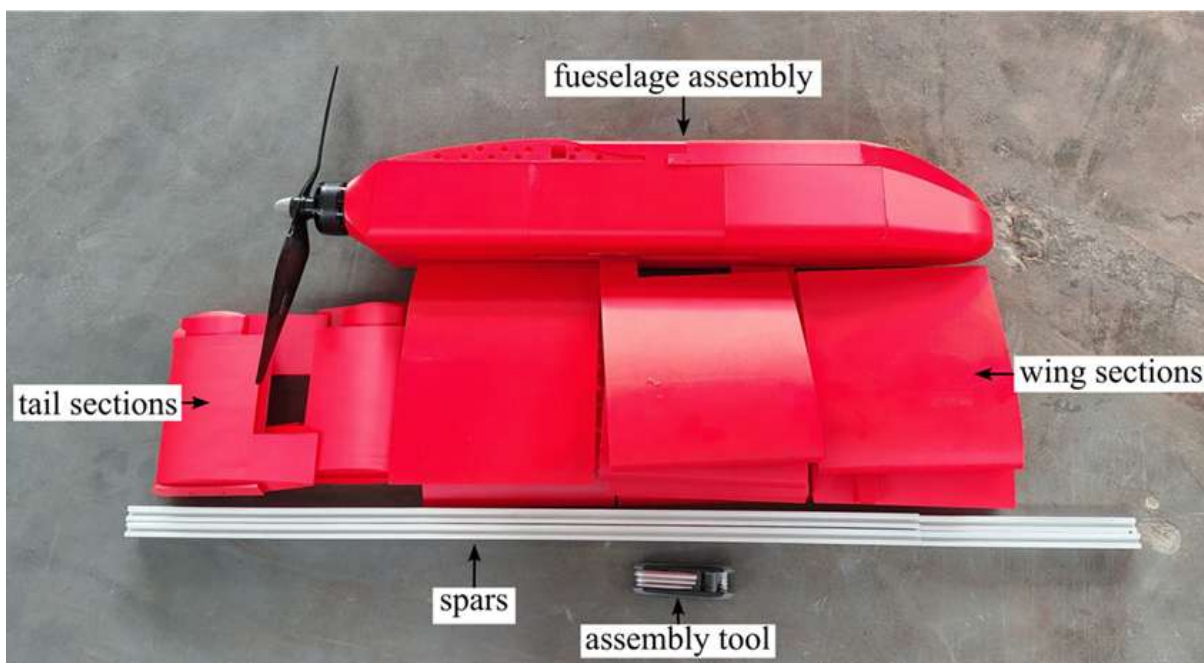
SWIFT-UAV Platform

- The SWIFT-UAV platform is designed to support a **high payload** capacity, ~20kg.
- It is an **affordable system**, making advanced UAV capabilities more accessible.



SWIFT-UAV Design

- The airframe is almost entirely **3D-printed**, with only the internal structural frame fabricated from lightweight **20×20 extrusion** to provide additional rigidity for payload integration and high-load maneuvers.



Filament	Model	Flushed	Total
1	1149.53 m 2737.28 g	0.00 m 0.00 g	1149.53 m 2737.28 g
2	936.95 m 2366.31 g	0.02 m 0.06 g	936.97 m 2366.37 g
Total	2086.48 m 5103.60 g	0.02 m 0.06 g	2086.50 m 5103.65 g
Total cost: 212.54			
Time Estimation			
Plate 1	12h14m		
Plate 2	13h50m		
Plate 3	12h21m		
Plate 4	10h30m		
Plate 5	7h3m		
Plate 6	6h51m		
Plate 7	13h50m		
Plate 8	10h2m		
Plate 9	12h20m		
Plate 10	10h30m		
Plate 11	7h3m		
Plate 12	6h51m		
Plate 13	4h58m		
Plate 14	4h28m		
Plate 15	4h22m		
Plate 16	4h28m		
Plate 17	4h27m		
Plate 18	1h50m		
Plate 19	1h50m		
Plate 20	1h7m		
Plate 21	7h52m		
Plate 22	7h16m		
Plate 23	3h21m		
Plate 24	3h21m		
Plate 25	1h28m		
Plate 26	2h14m		
Total	708h29m		

SWIFT-UAV

- The system is designed for **rapid field assembly**.



SWIFT as a Testbed

- The platform is **fully modular** and **open-source**, allowing users to customize components, integrate new technologies, and adapt the UAV for specialized tasks.
- **Various payloads** from separate research projects can be seen in the image.



Current Energy Management Limitations

- Battery constraints fundamentally **limit endurance and operational range**.
- Rigid voltage-threshold cutoffs reduce usable capacity, since high instantaneous loads cause voltage sag, **triggering early failsafe** limits even when significant charge remains.
- Conservative state-of-charge estimates are required.
- No predictive capability exists in typical UAV energy-management systems.

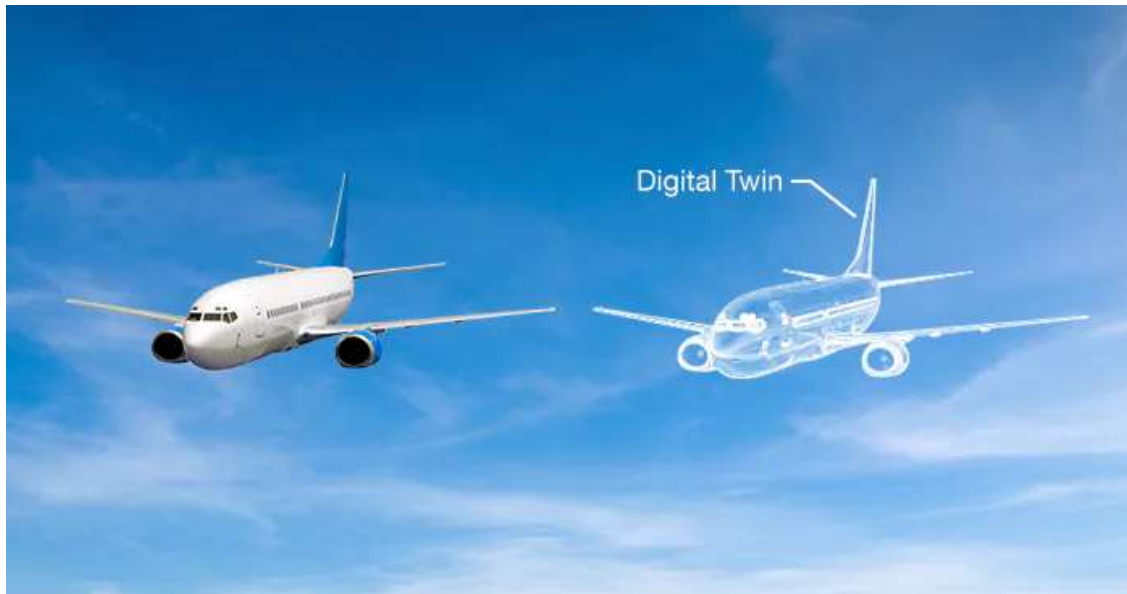
Battery constraint cause limits in flight time and range.

Voltage thresholds

Conservative estimates

No predictive capability

What is a Digital Twin?

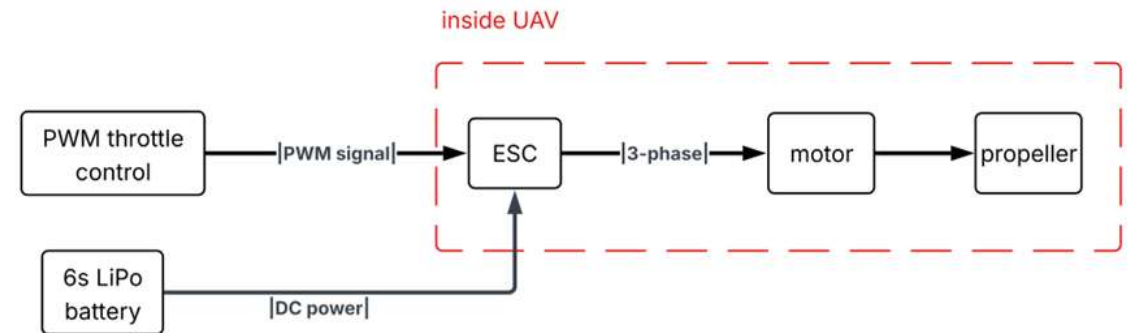


- A Digital Twin is a high-fidelity **computational model** that mirrors a physical UAV's behavior in real time.
- Live telemetry and sensor data continuously updates the model, ensuring the **virtual model remains synchronized** with the aircraft, enabling **accurate estimation of system states**.
- This real-time coupling allows **predictive analytics**, including anomaly detection, performance forecasting, and advanced **energy-management capabilities**.

[3] Figure 3 Digital Twins offer unmatched insights for design engineers, <https://www.mouser.com/applications/digital-twins-offer-insight/> (accessed Mar. 24, 2026).

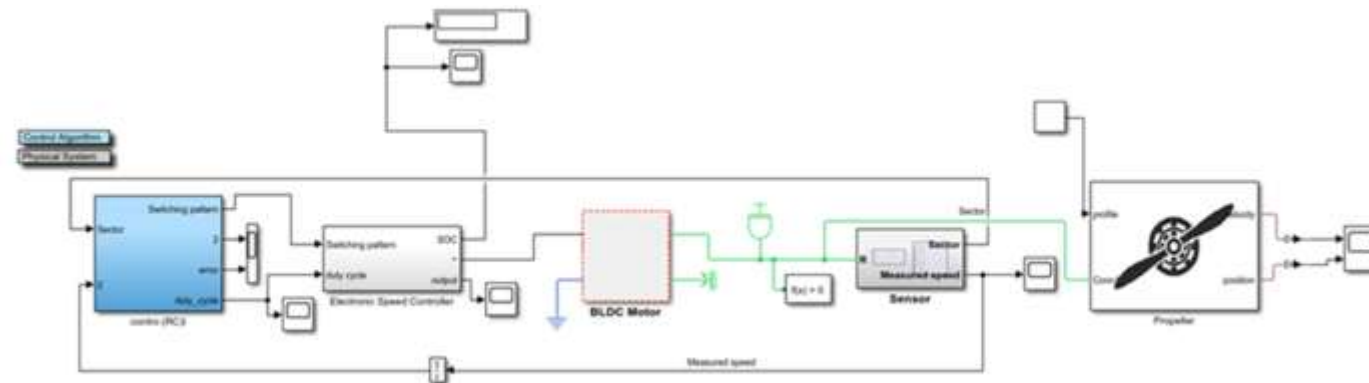
Approach

- The methodology consists of three main components:
 - Propulsion subsystem characterization
 - Digital twin model development
 - Experimental validation using an iron-bird test configuration
- The electrical subsystem is isolated to remove aerodynamic and flight-control uncertainties.
- Real-time voltage and current data are used for both model input and validation.



Digital Twin Model

- Implemented in MATLAB/Simulink using Simscape Electrical
- Composed of three subsystems:
 - Battery model (SOC-dependent voltage)
 - Motor–ESC model (PWM control, three-phase BLDC behavior)
 - Telemetry synchronization layer
- Captures nonlinear battery behavior and electromechanical coupling



Validation Strategy

The Digital Twin is exercised in simulation at three discrete throttle settings, generating predicted electrical, propulsion, and dynamic responses for each operating point.



The same throttle conditions are replicated on the Iron-Bird test configuration, allowing controlled, repeatable collection of real-world data.



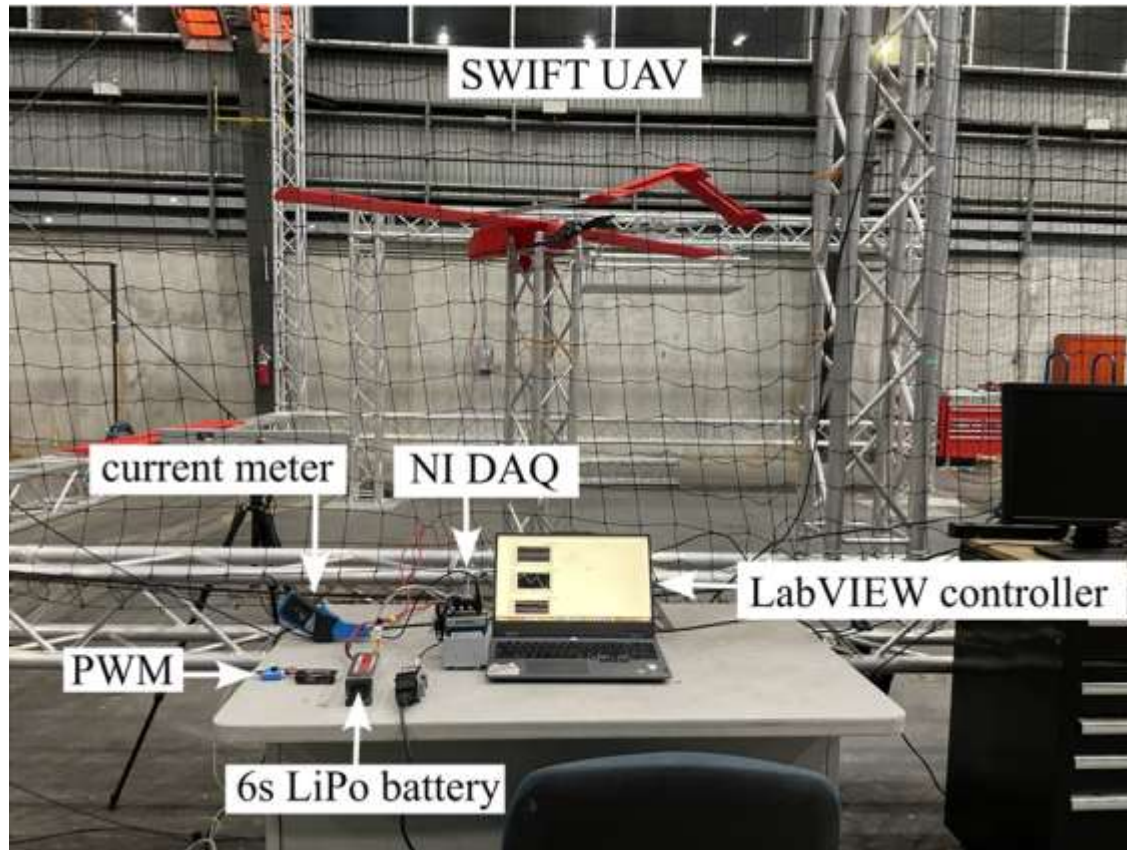
Simulated outputs are quantitatively compared against the Iron-Bird measurements to evaluate model accuracy, identify deviations, and tune system parameters.

Iron-Bird Configuration



- Ground-based propulsion test setup.
- The UAV is rigidly mounted to prevent motion.
- Isolates electrical system from aerodynamic effects enables repeatable testing across throttle conditions.

Experimental Setup

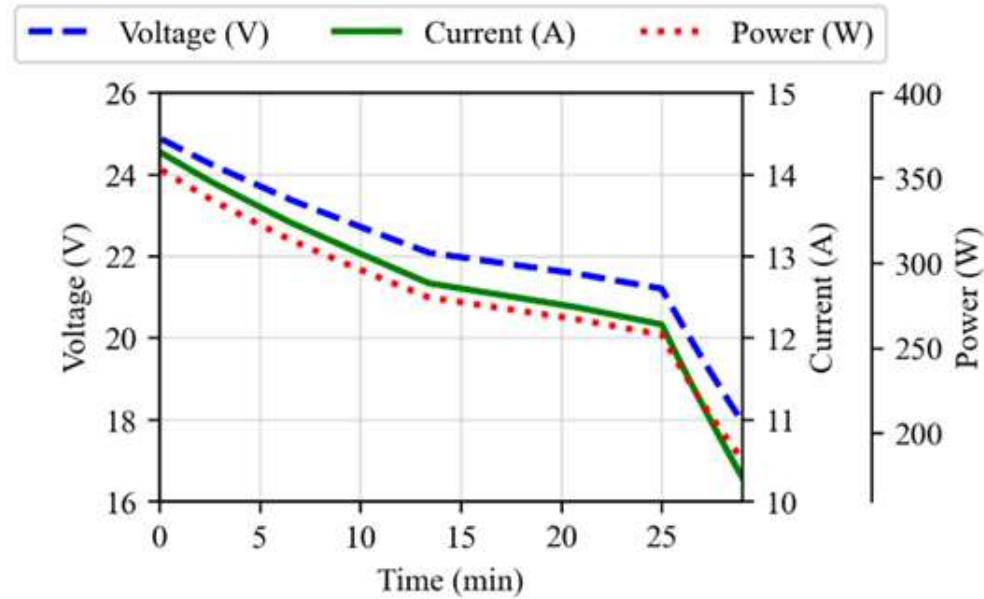


- 6S LiPo battery (6000 mAh, 100C)
- 120A ESC + BLDC motor + 21-inch propeller
- Voltage measured using NI 9221
- Current measured using CC-65 clamp + NI 9215
- Data acquisition through NI cDAQ-9174 and LabVIEW
- Sampling rate: 1 Hz

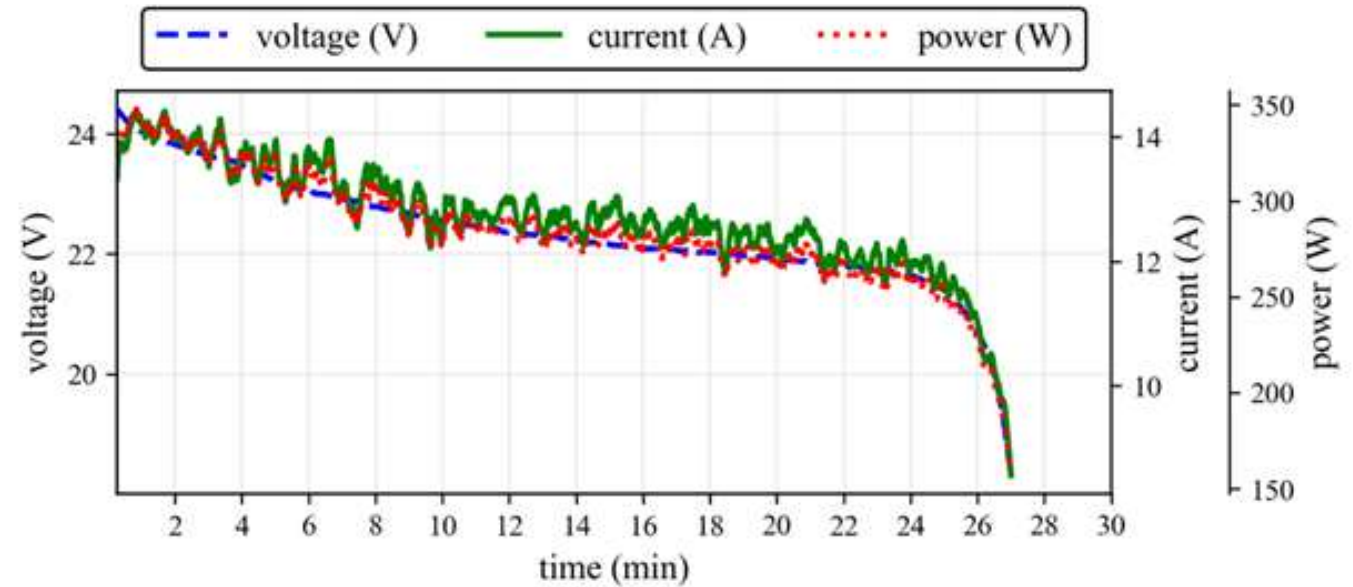
Results Overview

50% Throttle:

Simulation



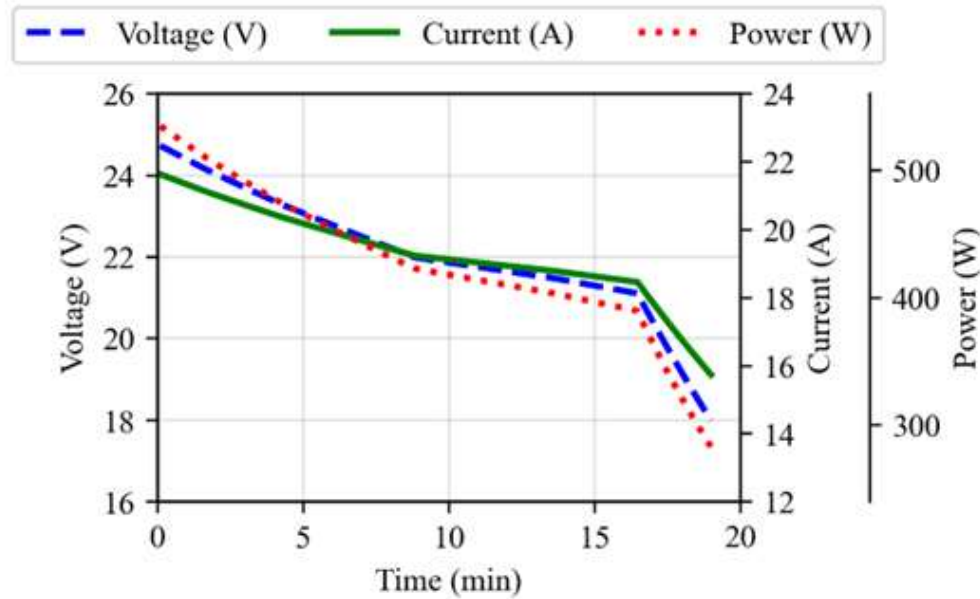
Iron Bird:



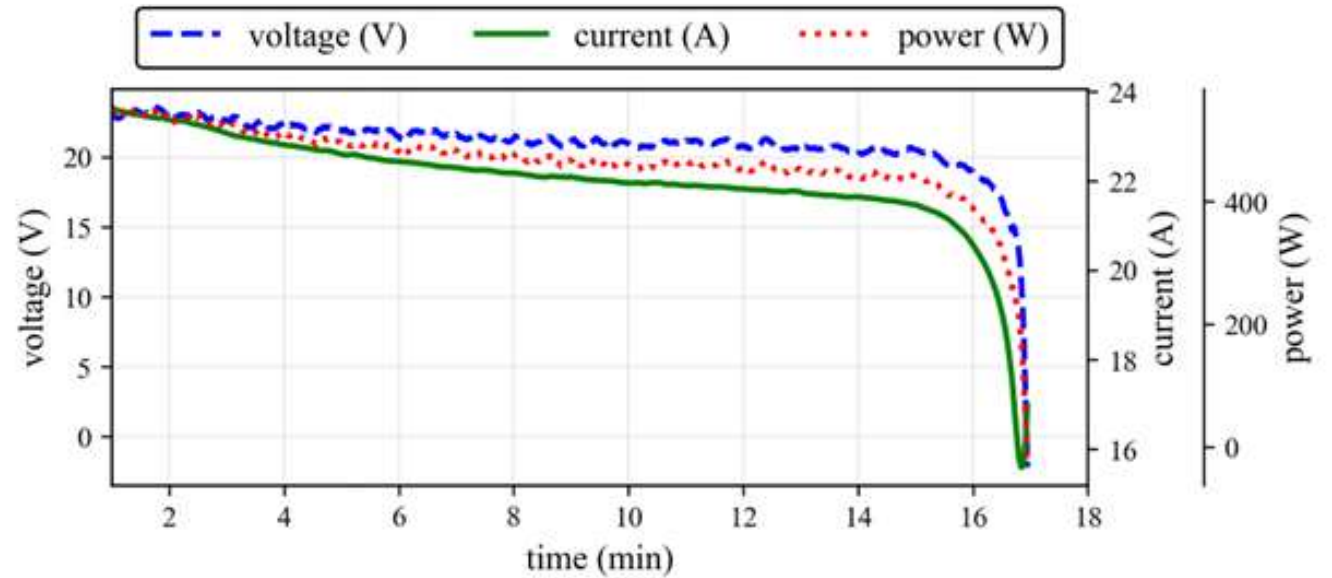
Results Overview

80% Throttle:

Simulation



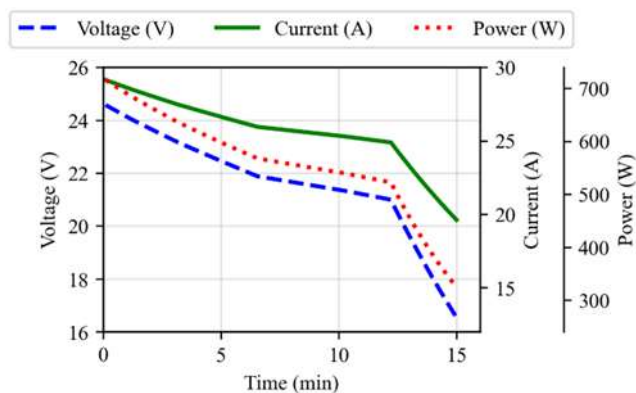
Iron Bird:



Results Overview

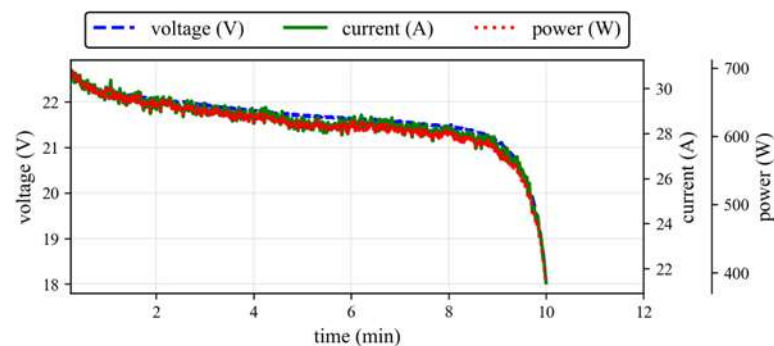
100% Throttle:

Simulation



- Endurance decreases consistently with increasing C-rate
- Digital twin **accurately captures load-dependent battery behavior**
- Model **remains stable** under moderate discharge conditions

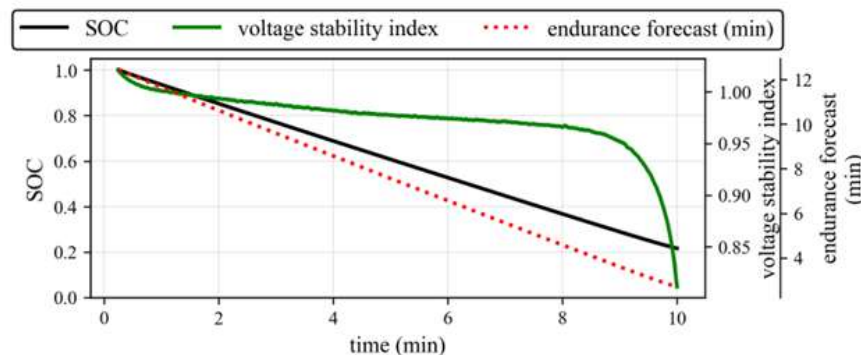
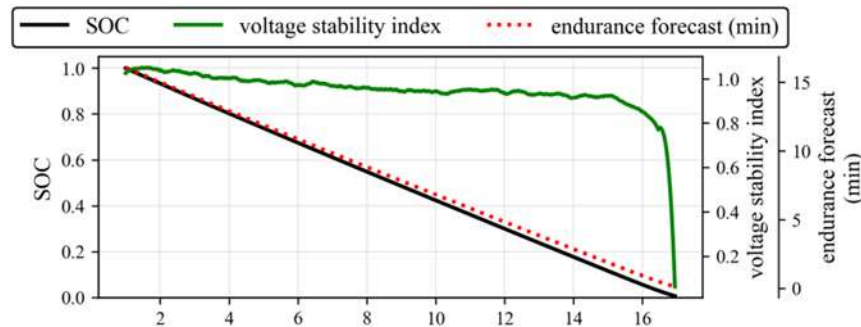
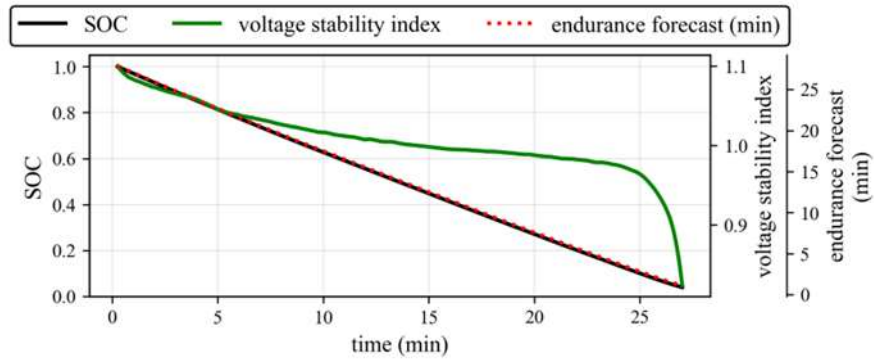
Iron Bird:



Throttle (%)	Avg. Current (A)	Energy (Wh)	Endurance Forecast (min)
50	12.701	127.000	33.5
80	22.019	123.762	20.4
100	28.423	99.993	15.1

Key Insight

- Digital twin successfully tracks state of charge (SOC) and predicts endurance under load
- Responds to changing throttle conditions
- Demonstrates transition from reactive monitoring to predictive energy management



Future Work

- Hardware-in-the-loop integration
- Full real-time onboard implementation
- In-flight validation of digital twin
- Higher voltage battery configurations (10S–12S)
- Extended-duration testing under realistic flight conditions

Acknowledgments

This work is supported by the ARTS Laboratory at the University of South Carolina and the National Science Foundation (NSF) under grant numbers ITE-2344357, CMMI2152896, and CPS2237696. Additional funding for this work comes from the Office of Naval Research through award number 14048906.

