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Remaining Useful Life digital shadow for an eVTOL Powertrain

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Abstract

This study introduces a real-time digital shadow representation for an electric Vertical Takeoff and Landing (eVTOL) powertrain, aimed at estimating the Remaining Useful Life (RUL) of key components. Leveraging real-time operational data, the digital shadow dynamically updates RUL estimates. The objective of this digital shadow is to enhance the reliability and maintenance strategies for eVTOL systems. The implementation encompasses critical components, including DC link capacitors, the motor, and the battery. Experimental results demonstrate the capability of the digital shadow to adjust RUL estimates in real-time in response to operational condition changes.

Introduction

Advancements in power electronics and energy storage technologies, driven by efforts to reduce operating costs and carbon emissions from commercial flights, have led to the emergence of various electrified aircraft concepts. The power systems of electric aircraft function as islanded DC microgrids in flight and connect to the terrestrial grid after landing to charge. The reduced size and cost of electric fan units enable their use in various locations on the aircraft in a distributed electric propulsion configuration, reducing noise emissions and fuel consumption [1]. A key example is the multi-rotor design in electric Vertical Take-off and Landing (eVTOL) aircraft [2].

Problem Statement

Reliability is paramount in aviation applications and maintenance intervals for conventional engines are mandated by the Federal Aviation Administration [3]. These fixed maintenance intervals are enabled by decades of turbine development and informed by massive amounts of flight data from hundreds of millions of commercial flights. Thanks to these factors, commercial aircraft engines are extremely reliable. The CFM56 turbofan used in airliners lasts 30,000 hours before maintenance is required, and the fleet of CFM56 engines have accumulated over 800 million flight hours [4]. No electric propulsion technology has come close to matching the flight time of these jet engines.

Solution

- A digital shadow is a faithful representation of a physical object, receiving data on its conditions and mirroring the real-time behavior of the physical object [5].
- A digital shadow serves as nominal baseline for comparison with its physical counterpart, identifying potential anomalies. For the purpose of this study, the digital shadow aids in dynamic Remaining Useful Life (RUL) estimation.
- To investigate the reliability and RUL of eVTOL powertrain components, a cyber-physical testbed featuring a single eVTOL rotor system was developed.
- The symmetry of the eVTOL powertrain enables the study of a single motor, motor drive, and its interconnection to the battery as the physical twin.
- Data from test flights and early commercial operations can be used more effectively by integrating it into a digital shadow.
- This paper provides an overview of this physical twin, its digital shadow overlay, the RUL models used in the digital shadow, and the experimental results.

Development of the Single-Rotor Testbed

To investigate the reliability and RUL of eVTOL power-train components, a cyber-physical testbed featuring a single eVTOL rotor system was developed. The cyber-system can be considered as layered, shown in Fig. 1. The physical twin hardware of the eVTOL powertrain consisted of a VFD, a motor, a dynomometer, and a battery emulator. The digital shadow computed the RUL of the DC bus capacitors, the battery, and the motor based on real-time operating data which was first verified with a transient powertrain model [6-10].

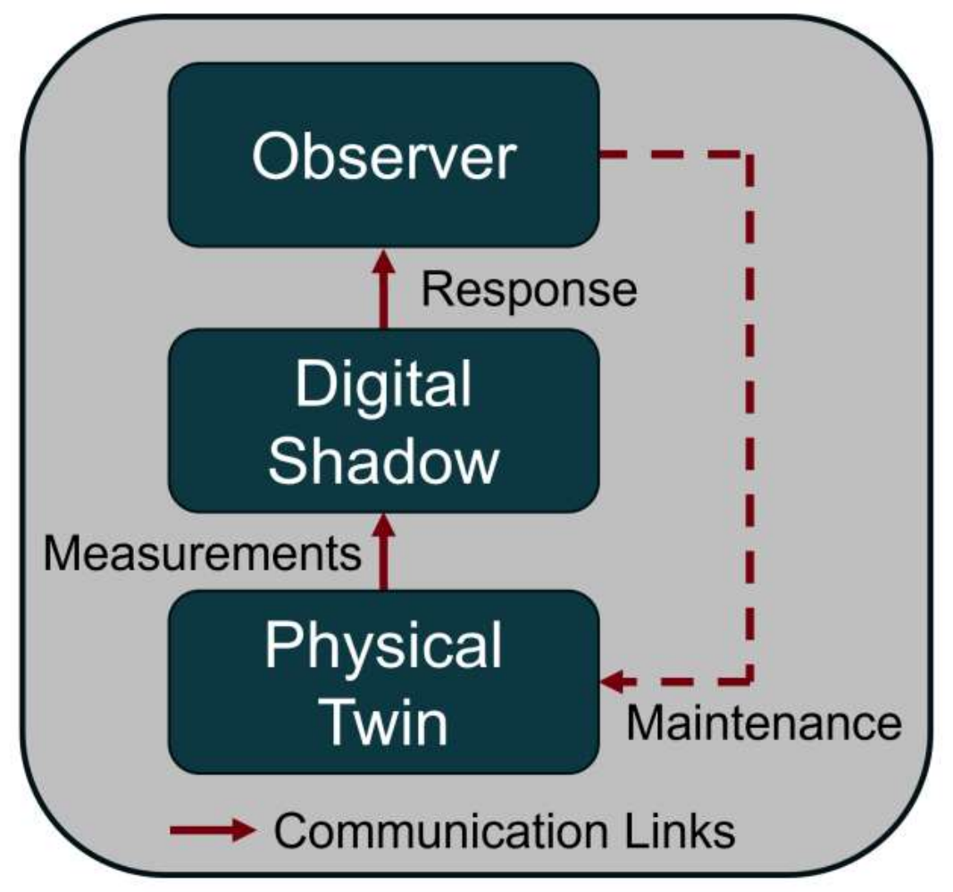

Fig. 1. Cyber-Physical system depicting the RUL digital shadow overlay.

- **Capacitor RUL:** Since the capacitors comprising the DC link were aluminum electrolytic capacitors, the capacitor RUL was estimated using the model presented in [8],

$$L = L_0 \left(\frac{V}{V_0}\right)^{-n} 2^{\frac{T_0 - T}{a}}$$

- **Motor RUL:** Motor RUL was calculated as a function of generated torque and time of operation. This approach was selected to allow the operator some freedom to preserve RUL by decreasing motor power while respecting current aviation industry practice of maintaining motors at fixed time intervals. The resulting model for motor RUL is

$$\mathrm{RUL}(t) = \mathrm{RUL}_0 - tK_m \left|\bar{\tau}_{em}\right|$$

- **Battery RUL:** Battery RUL was derived from charge/discharge cycles and an aging factor, which also factored into the State of Charge (SoC) calculations to reflect battery degradation [10]. The calculation was performed iteratively such that

$$\mathrm{RUL}[t] = \mathrm{RUL}[t-1] - \mathrm{RUL}_{adj}$$

Results and Discussion

The digital shadow was able to successfully mimic the speed and q-axis current regulation of the motor. This accurate response ensured the digital shadow was supplying inputs to RUL models comparable to those experienced by the real components. The agreement between the transient model and the hardware response is shown in Fig. 2. From only a load and speed setpoint, the transient model was able to accurately predict the speed, torque and power responses of the motor. These calculated quantities were then used as inputs to determine RUL of key system components.

The digital shadow was able to dynamically update RUL estimations in response to operating conditions, as shown in Fig. 3. This alignment highlights the effectiveness of the digital shadow in mirroring real-time operations and estimating component lifespans under varied operational conditions. A significant aspect of this digital shadow was its dynamic adaptation of the RUL estimations for the motor, which showed high responsiveness to operational changes. This feedback was particularly evident when the motor changed speed at 100 s. This event was captured by the slope reduction observed in the RUL plot within Fig. 3 following the speed reduction, and the corresponding drop in motor torque in the second half of the plot. Such responsiveness is essential for real-time monitoring and decision-making regarding in maintenance and operational strategies, positioning the digital shadow as a valuable predictive tool for eVTOL powertrain management

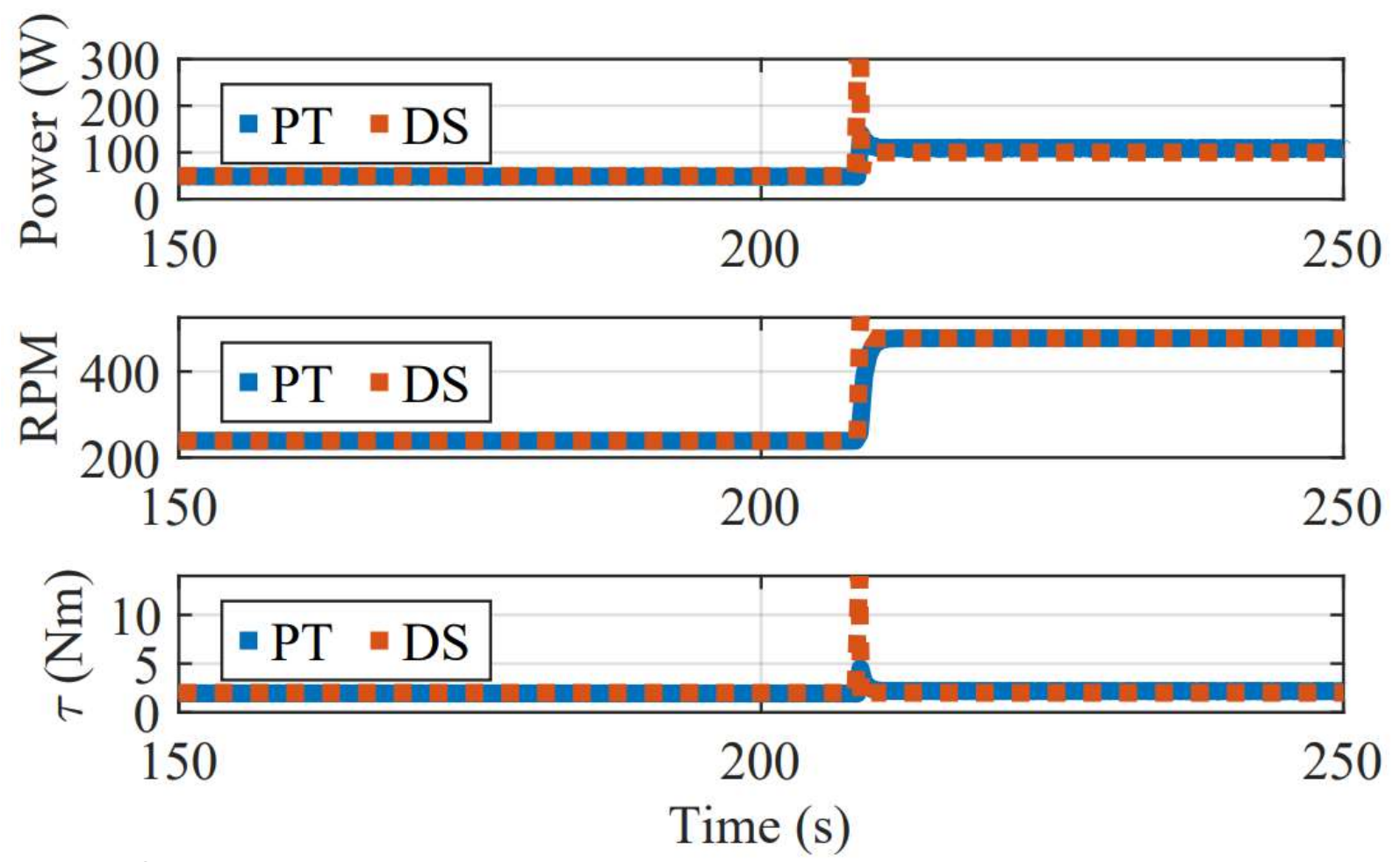

Fig. 2. Digital shadow transient model compared to hardware step response

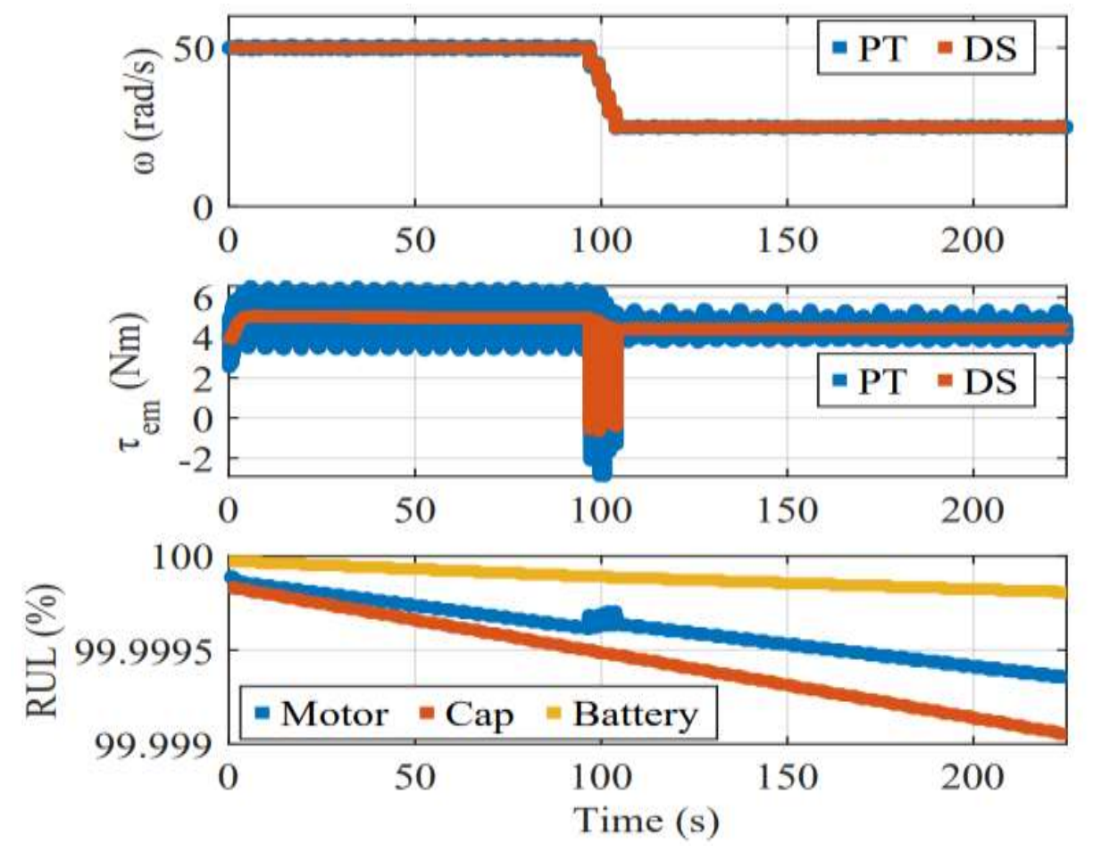

Fig. 3. RUL calculation for the motor, battery and DC link capacitors, and comparison of digital shadow to hardware.

Conclusions

- As eVTOLs approach commercialization, system reliability must be assured with far less flight data than has been accumulated for conventional aircraft. Rigorous system modeling applied in real-time as a digital shadow can help to bridge the gap.
- Digital shadows can protect people and property by warning system operators about degradation as a system operates in response to the actual operating condition of the aircraft and its historical utilization.
- This capability is a marked improvement over the fixed maintenance windows applied to conventional aircraft, which would be impossible to accurately specify for eVTOLs in the absence of more operational data.
- To improve the reliability assessment of key powertrain components, this work introduced a digital shadow representation for a single-rotor eVTOL powertrain testbed. A single rotor of an eVTOL power system was modeled to predict both the transient behavior of the system and the degradation of key components.
- By replicating the motor control system and providing an average model of the motor and VFD, the speed, torque, and power load of the motor throughout a flight profile was predicted in real-time.
- Using the results of the transient model, the digital shadow provided continuous RUL estimates for the motor, DC link capacitors, and the battery. These insights, essential for predictive maintenance, were made accessible to operators for informed real-time decision-making on system maintenance and operational adjustments.

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