

# **Compact Electromechanical Actuators for Urban Air Mobility:**

## Development of a Framework for Design, Digital Twin and PHM Integration in eVTOL Aircrafts

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Urban Air Mobility (UAM) represents a transformative solution to urban challenges such as traffic congestion and pollution, leveraging electric propulsion and automated technologies. The large-scale deployment of this technology relies on electric Vertical Takeoff and Landing (eVTOL) vehicles, which require highly efficient and reliable flight control systems. Compact electromechanical actuators (cEMAs) play a crucial role in this context, offering lightweight and space-efficient control solutions. However, they retain inherent reliability challenges associated with electromechanical actuation. This dissertation presents a comprehensive framework for the design, high-fidelity modeling, and Prognostics and Health Management (PHM) integration of cEMAs for eVTOL systems, addressing key aspects of performance, safety, and operational reliability.

The research underscores the increasing significance of UAM and eVTOL technologies and their critical components, highlighting trends in global scientific advancements and regulatory developments by EASA and FAA. The proposed framework integrates progress across multiple disciplines, including high-fidelity modeling of components such as harmonic drive reducers and advanced safety assessment methodologies. The study includes an extensive literature review covering the historical and regulatory evolution of UAM, alongside a systematic approach to actuator design, from requirement definition to the integration of PHM techniques.

Central to this research is the application of System Safety Assessment (SSA) methodologies, including Failure Modes, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA). These techniques ensure the safe integration of cEMAs into eVTOL systems by systematically identifying failure modes, evaluating their impacts, and defining mitigation strategies. The integration of SSA with PHM enables early fault detection, predictive

diagnostics, and risk minimization, significantly enhancing safety and reliability.

A key contribution of this work is the development of high-fidelity analytical models for PHM and digital twin applications. These models incorporate both linear and nonlinear representations of the actuator system, enabling fault injection and non-nominal behavior simulation. In particular, a novel harmonic drive reducer (HDR) model is proposed, balancing computational efficiency with the ability to capture complex nonlinear dynamics such as backlash and wear. The proposed modeling approach is validated through extensive simulation campaigns, assessing actuator behavior under various operational conditions and extracting health features from sensor signals for pre-flight and in-flight diagnostics.

The findings of this research demonstrate the transformative potential of integrating advanced modeling and PHM techniques into actuator design and health management. The proposed framework contributes significantly to the development of safe, reliable, and sustainable urban air transportation systems, laying the groundwork for the future of UAM.