

Review

Electromechanical Flight-Control Actuation Systems for More-Electric Aircraft: Architectures, Energy-Efficiency Trade-Offs, Fault Tolerance, and Future Challenges

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Abstract

The transition to more-electric aircraft (MEA) is driving the replacement of centralized hydraulic and pneumatic systems with electrically powered alternatives. Within this paradigm, flight-control actuation remains one of the most demanding subsystems, combining strict requirements in force density, dynamic response, reliability, fault tolerance, thermal performance, and certification. Electromechanical actuators (EMAs) are a key enabling technology due to their potential for power-on-demand operation, reduction or elimination of hydraulic infrastructure, improved maintainability, and compatibility with distributed electrical architectures. However, their broader use in safety-critical flight-control applications remains constrained by mechanical jamming, thermal management, power-electronics robustness, fault tolerance, health monitoring, and system-level integration. This paper presents a structured, design-oriented review of electromechanical flight-control actuation systems within the MEA framework. It analyzes the evolution from hydraulic to fully electromechanical actuation, examines EMA architectures and subsystems, reviews energy-efficiency trade-offs at actuator and aircraft levels, and discusses fault modes, redundancy strategies, fault-tolerant design, and health-monitoring approaches. Finally, it identifies open challenges related to certification, jamming mitigation, high-voltage electrical architectures, wide-bandgap power electronics, thermal management, and digital twin-based health monitoring. The review provides a unified system-level perspective that supports the development of energy-efficient, fault-tolerant, and certifiable flight-control actuation systems.

Keywords: more-electric aircraft (MEA); electromechanical actuator (EMA); flight control actuation; energy-efficiency trade-offs; fault tolerance; power electronics; thermal management; health monitoring; aircraft electrification



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1. Introduction

The aviation sector is undergoing a progressive electrification of onboard systems driven by energy-efficiency, reliability, maintainability, and environmental objectives. In the more-electric aircraft (MEA) paradigm, this transition affects not only propulsion-related functions but also non-propulsive subsystems such as environmental control, ice protection, braking, landing gear, and flight-control actuation [1–3]. Among these subsystems, flight-control actuation is especially demanding because it directly influences aircraft safety, controllability, aerodynamic performance, and mission-level energy consumption.

Flight-control actuators drive primary control surfaces, such as ailerons, elevators, and rudders, as well as secondary surfaces, including flaps, slats, spoilers, and trim systems.

Historically, actuation evolved from mechanical linkages to centralized hydraulic systems as the size, speed, and aerodynamic loads of the aircraft increased. Servo-hydraulic actuators (SHAs) therefore became the dominant solution due to their force density, dynamic response, robustness, and certification maturity [4–6].

However, the advantages of hydraulic actuation at component level are accompanied by aircraft-level penalties. Centralized hydraulic architectures require continuous pressurization, distributed pipework, reservoirs, pumps, valves, filters, fluid maintenance, and leakage prevention. These elements increase weight and maintenance effort and create parasitic losses even when individual actuators are inactive [1,2,6,7]. This system-level perspective has motivated the gradual introduction of electrified actuation technologies.

Electro-hydrostatic actuators (EHAs) and electro-backup hydraulic actuators (EBHAs) represent transitional architectures. EHAs generate hydraulic power locally through an electric motor-pump unit, reducing centralized hydraulic distribution and enabling power-on-demand behavior. EBHAs retain conventional hydraulic operation, but add an electrical backup path, improving different redundancy and supporting incremental electrification [8–10]. These concepts reduce some hydraulic penalties, but still retain fluid-based components and local thermal-management challenges.

Electromechanical actuators (EMAs) go further by eliminating hydraulic conversion and transforming electrical energy directly into mechanical motion through motors, power electronics, control units, sensors, and mechanical transmissions. Linear EMAs commonly use ball screws or planetary roller screws to convert rotary motion into surface displacement. Their potential advantages include power-on-demand operation, absence of hydraulic leakage, distributed control, improved observability for health monitoring, and compatibility with high-voltage electrical networks and advanced power electronics [11–17].

Figure 1 illustrates the main flight-control actuator architectures considered in this review, from conventional servo-hydraulic actuation to hybrid electro-hydraulic solutions and fully electromechanical actuation. The comparison highlights the progressive shift from centralized hydraulic power distribution toward local electrical energy conversion, embedded power electronics, and distributed actuator control.

The same architectural shift also introduces the main barriers to safety-critical adoption. In particular, screw-based transmissions may jam, and a mechanical blockage can directly restrict the associated control surface. Other relevant limitations include wear, backlash, lubrication degradation, bearing failures, motor and winding faults, power-electronics failures, sensor faults, thermal overload, control-channel failures, and electromagnetic compatibility constraints [18–23]. As a result, EMA design must address efficiency and integration together with fault tolerance, health monitoring, degraded-mode operation, and certification.

Although aircraft actuation technologies have been widely studied, the literature often treats hydraulic, electro-hydrostatic, and electromechanical solutions separately, or focuses on individual EMA subsystems. A more integrated view is needed because the transition to EMAs involves aircraft-level mass and power distribution, thermal management, redundancy allocation, maintainability, failure propagation, prognostics and health management (PHM) capability, and certification evidence.

Therefore, this paper presents a design-oriented review of electromechanical flight-control actuation systems for MEA, integrating architecture selection, energy-efficiency trade-offs, fault-tolerant design, thermal constraints, power-electronics integration, health monitoring, and certification challenges into a unified system-level framework. The review traces the transition from hydraulic to fully electric actuation, analyzes EMA subsystems, compares actuation technologies from an energy-efficiency perspective, re-

views failure modes and redundancy strategies, and identifies open challenges for safety-critical adoption.

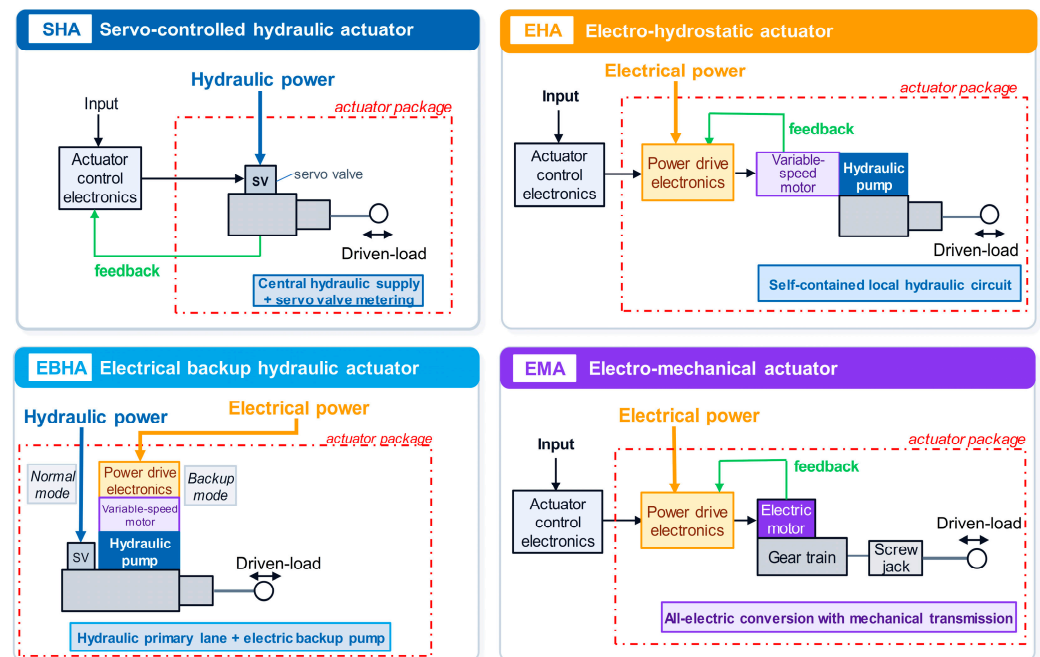


Figure 1. Schematic comparison of the main flight-control actuator architectures considered in this review: servo-hydraulic actuator (SHA), electro-hydrostatic actuator (EHA), electro-backup hydraulic actuator (EBHA), and electromechanical actuator (EMA). The figure highlights the transition from centralized hydraulic power distribution toward local electro-hydraulic conversion and fully electro-mechanical actuation, as well as the increasing role of embedded power electronics, sensing, and actuator-level control.

The main contributions of this review can be summarized as follows:

- It provides a comparative overview of conventional, hybrid, and fully electromechanical flight-control actuation technologies.
- It relates EMA subsystem design to aircraft-level efficiency, integration, reliability, and maintainability constraints.
- It synthesizes the main failure mechanisms, redundancy options, and fault-tolerant strategies relevant to safety-critical EMA applications.
- It identifies technological and certification barriers that must be addressed for broader EMA adoption in next-generation aircraft.

By addressing these aspects together, this paper clarifies the conditions under which EMAs can contribute to safer, lighter, more maintainable, and more energy-efficient flight-control architectures, while also identifying the remaining barriers that prevent straightforward replacement of mature hydraulic systems.

2. Review Methodology

This paper was conducted as a structured and design-oriented narrative review focused on electromechanical flight-control actuators for more-electric aircraft. The objective was not to perform a fully systematic review, bibliometric or quantitative meta-analysis, but to identify, organize, and critically synthesize technical contributions relevant to EMA architecture, aircraft-level integration, energy efficiency trade-offs, fault tolerance, health monitoring, thermal management, and certification-oriented design.

The literature search covered scientific and technical publications available up to June 2026. The main sources consulted were Scopus, Web of Science and IEEE Xplore. In

addition, backward and forward reference-chain searches were used to identify relevant books, aerospace standards, technical reports, doctoral theses, and technical documentation not always fully indexed in scientific databases.

The search strategy combined terms related to aircraft electrification, actuation technologies, safety, energy efficiency, monitoring, and certification. Representative search strings included combinations of the following terms: “More Electric Aircraft”, “all-electric aircraft”, “aircraft electrification”, “flight-control actuator”, “control surface actuator”, “electromechanical actuator”, “EMA”, “servo-hydraulic actuator”, “electro-hydrostatic actuator”, “electro-backup hydraulic actuator”, “energy efficiency”, “jamming”, “fault tolerance”, “redundancy”, “common-cause failure”, “health monitoring”, “prognostics”, “digital twin”, “power electronics”, “wide-bandgap devices”, “thermal management”, “reliability”, and “certification”.

The search was intentionally broad because electromechanical flight-control actuation is a multi-domain topic involving aircraft systems, mechanical transmissions, electric machines, power electronics, control, reliability, PHM, thermal management, and certification. Hydraulic and hybrid electro-hydraulic actuation technologies were also included to provide a comparative baseline for fully electromechanical architectures.

Studies were retained when they addressed aircraft flight-control actuation technologies, EMA subsystem design, hydraulic/electro-hydraulic/electromechanical actuator comparison, energy-efficiency mechanisms, mechanical jamming, fault-tolerant architectures, redundancy strategies, power-electronics integration, motor-drive design, thermal management, PHM, digital twins, or certification issues relevant to safety-critical aerospace actuation.

Studies were excluded when they focused only on propulsion, non-aerospace industrial actuators, low-power robotic actuators not representative of aircraft flight-control requirements, or commercial descriptions without sufficient technical content. Duplicate sources, sources without accessible technical detail, and publications unrelated to flight-control actuation were also removed from the synthesis.

The selected literature was classified according to actuator technology, EMA subsystem, performance dimension, failure domain, monitoring approach, and application level. The actuator technologies considered were SHA, EHA, EBHA, and EMA. EMA subsystems were grouped into mechanical transmissions, electric motors, power electronics, sensors, control units, and thermal-management elements. Fault-related studies were organized by dominant failure mechanism, including jamming, backlash, wear, lubrication degradation, bearing faults, motor faults, power-electronics faults, sensor faults, control faults, and common-cause failures. PHM approaches were classified as model-based, signal-based, current-based, vibration-based, data-driven, AI-based, or digital-twin-based methods.

Because EMA performance depends strongly on aircraft class, control-surface type, load profile, duty cycle, cooling assumptions, redundancy architecture, and certification requirements, this review does not attempt to provide a universal quantitative ranking of actuator technologies. Instead, quantitative values and representative ranges are included where reliable literature data are available, while qualitative comparisons are explicitly identified as relative, technology-level assessments. The scope is limited to electromechanical actuators and related actuation technologies for aircraft flight-control applications. Detailed mathematical modeling and simulation of EMA dynamics are beyond the scope of this review.

Table 1 summarizes the methodological framework adopted in the review.

Table 1. Methodological framework used for the structured, design-oriented narrative review.

Category	Description
Review type	Structured, design-oriented narrative review.
Main objective	Critical synthesis of EMA technologies for MEA flight-control applications, with emphasis on architecture, aircraft-level integration, energy-efficiency trade-offs, fault tolerance, PHM, thermal management, and certification-oriented design.
Search period	Publications available up to June 2026.
Databases and sources	Scopus, Web of Science, IEEE Xplore, reference-chain searches, books, standards, technical reports, and theses.
Search strategy	Keyword combinations related to aircraft electrification, flight-control actuation, SHA, EHA, EBHA, EMA, energy efficiency, jamming, fault tolerance, redundancy, PHM, digital twins, power electronics, thermal management, reliability, and certification.
Main technologies	SHA, EHA, EBHA, and EMA technologies.
Main dimensions	Architecture, mechanical transmission, motors, power electronics, sensing, control, energy efficiency, thermal management, failure modes, redundancy, PHM, digital twins, validation maturity, and certification.
Inclusion criteria	Sources addressing aircraft flight-control actuation, EMA subsystems, MEA integration, energy-efficiency mechanisms, mechanical jamming, redundancy, fault tolerance, PHM, thermal issues, or certification-relevant aerospace actuation
Exclusion criteria	Propulsion-only studies, non-aerospace industrial actuators, low-power robotic actuators not representative of aircraft flight-control requirements, commercial descriptions without sufficient technical content, duplicate sources, and sources outside flight-control actuation.
Synthesis approach	Thematic classification by actuator technology, subsystem, performance dimension, failure domain, monitoring approach, and application level.
Nature of comparisons	Mainly qualitative and design-oriented; representative quantitative values or ranges are included where reliable and comparable literature data are available.
Scope limitation	The review is limited to electromechanical actuators and related actuation technologies for aircraft flight-control applications; detailed mathematical modeling and simulation of EMA dynamics are outside its scope.

Note: The table summarizes the review protocol used to support a structured narrative synthesis. It is not intended to imply a PRISMA-style systematic review, bibliometric analysis, or quantitative meta-analysis.

3. Evolution of Flight-Control Actuation Technologies

Aircraft flight-control actuation has evolved from mechanical linkages to centralized hydraulic systems, hybrid electro-hydraulic concepts, and fully electromechanical solutions. This evolution has been driven by increasing aerodynamic loads, safety requirements, controllability demands, maintenance constraints, and the search for aircraft-level energy savings.

This section compares the main actuation technologies considered in this review: SHAs, EHAs, EBHAs, and EMAs. The emphasis is placed on how each architecture generates, distributes, and converts power, and on the resulting trade-offs in efficiency, reliability, fault tolerance, integration, and MEA compatibility. A comparative synthesis of these technologies is provided at the end of the section.

3.1. Servo-Hydraulic Actuators

Servo-hydraulic actuators have been the reference technology for aircraft flight-control systems for several decades because they provide high force capability, high power density, fast response, robustness, and extensive operational experience in safety-critical applications [4–6]. In conventional architectures, centralized pumps, reservoirs, accumulators, valves, and distribution lines supply pressurized fluid to multiple actuators, while servo-valves regulate the pressure difference across each actuator piston.

At the actuator level, SHAs offer excellent bandwidth, force control, and certification maturity, making them suitable for both primary and secondary flight-control surfaces. Their main limitation appears at the system level: continuous pressurization, servovalve throttling, leakage compensation, pipe pressure drops, fluid maintenance, and distributed hydraulic infrastructure generate weight, complexity, and parasitic losses even when individual actuators are inactive [1,2,6,7].

Therefore, in the MEA context, SHAs remain highly mature and reliable, but are increasingly challenged by aircraft-level efficiency and maintainability objectives. Their limitations provide the baseline against which electrified and fully electric actuation technologies are assessed.

3.2. Electro-Hydrostatic Actuators

Electro-hydrostatic actuators replace the centralized hydraulic supply with locally generated hydraulic power. A typical EHA integrates an electric motor, hydraulic pump, local hydraulic circuit, and actuator cylinder in a self-contained unit [6,8,9]. Therefore, the actuator draws electrical power and produces hydraulic power only when surface motion is required.

This power-on-demand behavior reduces standby losses and hydraulic distribution complexity while retaining key hydraulic advantages such as high force density and load capacity [6,8,9,24]. EHAs also improve modularity and fault isolation, which makes them attractive for MEA architectures that seek to reduce centralized hydraulic networks without completely abandoning hydraulic actuation.

The penalty is an increase in local complexity. EHAs combine motors, converters, pumps, valves, seals, fluid circuits, and thermal paths in a compact unit, creating additional failure modes and heat concentration. They are therefore best understood as an intermediate technology: they improve aircraft-level efficiency relative to centralized hydraulics, but do not eliminate hydraulic maintenance and thermal constraints.

3.3. Electro-Backup Hydraulic Actuators

Electro-backup hydraulic actuators combine conventional hydraulic operation with an electrically driven backup path. Under normal conditions, the actuator behaves as an SHA supplied by the centralized hydraulic system; after certain hydraulic failures, an integrated motor-pump unit can provide local hydraulic power to preserve actuator functionality [5,6,10,11].

A representative implementation is the Airbus A380 flight-control architecture, where electrically powered actuators were introduced together with conventional hydraulic actuators to provide hydraulic/electrical dissimilarity and additional redundancy in a

more-electric configuration [25]. This illustrates the main rationale for EBHAs: improving availability and certification confidence during the transition toward electrified actuation.

Because EBHAs retain the hydraulic path during normal operation, their efficiency benefit is limited compared to EHAs or EMAs. Their value is primarily architectural and safety-related: they allow designers to introduce electrical backup capability while preserving much of the maturity and performance of hydraulic actuation.

The drawback is that EBHAs add components, mass, interfaces, and failure modes. Therefore, they should be viewed mainly as a conservative, certification-driven transition technology rather than as a purely efficiency-driven solution.

3.4. Electromechanical Actuators

Electromechanical actuators eliminate hydraulic power conversion and generate controlled motion through an electric motor, power electronics, sensors, control electronics, and mechanical transmission [10–13]. In linear flight-control applications, motor rotation is usually converted into translational motion by ball-screw or planetary-roller-screw mechanisms, often with an intermediate gearbox depending on the force and speed requirements.

From a system perspective, EMAs move the main engineering problem from hydraulic power management to integrated electrical, mechanical, thermal, and control design. They support power-on-demand operation, remove hydraulic leakage, simplify some maintenance activities, and fit naturally within distributed electrical architectures. Advances in permanent-magnet machines, high-power-density converters, wide-bandgap devices, and high-voltage DC systems further increase their feasibility [14–17].

Their main barriers are also system-level. Mechanical jamming, transmission wear, backlash, lubrication degradation, bearing faults, motor and converter failures, sensor faults, control malfunctions, electromagnetic interference (EMI)/electromagnetic compatibility (EMC) issues, and heat concentration can directly affect the availability of the control surface. These effects are especially critical for primary flight controls, where a jammed or unavailable actuator may compromise controllability.

Consequently, the adoption of EMA requires more than replacing a hydraulic actuator with an electric unit. It requires mechanical jam mitigation, redundant or reconfigurable motor-drive architectures, robust sensing and control, thermal co-design, health monitoring, and certification evidence for degraded operation.

3.5. Comparative Synthesis and Transition

Therefore, the transition from SHAs to EHAs, EBHAs, and EMAs reflects a shift from centralized hydraulic power to distributed electrical actuation. SHAs provide maturity and high force density but carry aircraft-level hydraulic penalties. EHAs reduce these penalties through local power generation, while EBHAs mainly add a different backup capability. EMAs offer the strongest route to fully electric actuation, but introduce new mechanical, electrical, thermal, and certification challenges.

Table 2 summarizes these differences by comparing the main architectural, efficiency, reliability, maintenance, and certification characteristics of SHAs, EHAs, EBHAs, and EMAs.

Among these technologies, EMAs concentrate the highest level of architectural integration, which motivates a more detailed analysis of their internal structure and design constraints.

The central design trade-off is therefore not simply hydraulic versus electric power. It is the balance between aircraft-level efficiency, actuator-level mass, thermal feasibility, failure behavior, redundancy, maintainability, and certification maturity. The following

sections analyze these trade-offs from the internal EMA architecture to the aircraft-level energy and safety case.

Table 2. Comparative analysis of flight-control actuation technologies. The comparison is qualitative and design-oriented, based on the synthesis of the cited literature.

Feature	SHA	EHA	EBHA	EMA
Energy source	Centralized hydraulic	Electrical + local hydraulic	Central hydraulic + electrical backup	Electrical
Hydraulic dependency	Full	Local	Partial	None
Energy efficiency (system-level)	Low	Medium	Medium	High
Power-on-demand capability	No	Yes	Partial	Yes
Power distribution	Centralized	Distributed (local generation)	Centralized + local backup	Fully distributed
Actuator complexity	Medium	High	High	Medium
System complexity	High (hydraulic network)	Medium–High	High	Medium
Force capability / power density	Very high	High	Very high	High
Thermal management complexity	Low–Medium	High	Medium–High	High
Fault tolerance	High	High	Very high	Medium
Redundancy approach	Multiple hydraulic circuits	Local redundancy	Electrical + hydraulic redundancy	Electrical/architectural redundancy
Failure criticality (jamming)	Low (bypass possible)	Low–Medium	Low	High
Maintenance requirements	High	Medium	Medium	Low–Medium
Leakage risk	High	Medium	Medium	None
Integration with MEA architecture	Low	Medium–High	Medium	High
Certification maturity	Very high	High	High	Medium
Technology maturity (TRL)	Very high	High	High	Medium–High
Typical applications	Primary & secondary controls	Primary/secondary (modern aircraft)	Safety-critical surfaces	Increasingly secondary → future primary

Note: The descriptors Low, Medium, High, and Very High indicate relative tendencies among the actuator technologies considered in this review, not absolute numerical rankings. They are based on the synthesis of the cited literature and refer to technology-level behavior under representative aerospace flight-control requirements. Actual values depend on aircraft class, surface type, actuator sizing, duty cycle, redundancy architecture, and thermal-management assumptions.

4. Electromechanical Actuators in More-Electric Aircraft

Having established the role of EMAs in the evolution of aircraft actuation, this section examines their internal architecture and design constraints. In flight-control applications, an EMA is an integrated actuation system rather than a single component: it combines power conversion, motor control, mechanical transmission, sensing, protection, thermal paths, and often redundancy or fault-isolation mechanisms.

Key architectural choices, such as geared versus direct-drive layouts, ball screws versus planetary roller screws, conventional versus multiphase motors, and single-channel versus

redundant power electronics, directly affect mass, efficiency, reliability, maintainability, fault tolerance, and certification effort [10–14,26].

4.1. Functional Architecture of an EMA

The functional architecture of a flight-control EMA can be described through the energy path from the electrical network of the aircraft to the aerodynamic control surface. Electrical power is supplied by the aircraft power distribution system and is conditioned by the actuator power electronics. The electric motor converts this controlled electrical power into torque, whereas the mechanical transmission adapts the motor output to the force, speed, and displacement required by the control surface.

Figure 2 illustrates the functional architecture of a typical electromechanical actuator for flight-control applications, highlighting the main energy conversion stages (from the electrical power supply of the aircraft to the mechanical actuation of the load) as well as the embedded sensing elements used for feedback control, protection, and condition monitoring.

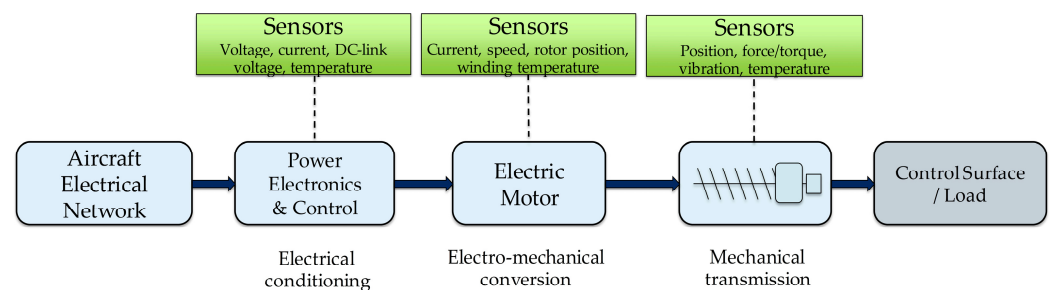


Figure 2. Functional architecture of an electromechanical actuator for flight-control applications. The diagram shows the energy path from the aircraft electrical network to the control surface or load, including power electronics and control, electric motor, mechanical transmission, and embedded sensing. The measured variables support feedback control, protection, fault detection, and health monitoring.

Position feedback is usually provided by resolvers, encoders, rotary variable differential transformers (RVDTs), or linear variable differential transformers (LVDTs), whereas current, voltage, temperature, and vibration measurements support protection and condition monitoring. The actuator control unit typically combines current or torque control with speed and position loops. In safety-critical applications, these nominal control functions must be complemented by fault detection, protection logic, reconfiguration strategies, and health-monitoring functions.

4.2. Mechanical Transmission Systems

The mechanical transmission is one of the most critical subsystems of a flight-control EMA. Its function is to convert the high-speed, relatively low-torque output of the electric motor into the low-speed, high-force motion required by the control surface. For linear actuators, this conversion is normally achieved using screw-based mechanisms, often combined with a gearbox depending on the required force, speed, stroke, installation envelope, and motor technology. Two main transmission approaches can be distinguished: geared-drive and direct-drive architectures. Geared-drive EMAs use a reduction gearbox between the motor and the screw mechanism. This allows the use of compact high-speed motors and can improve torque matching, but increases mechanical complexity and may introduce additional losses, backlash, wear, and failure modes. Direct-drive EMAs eliminate the gearbox, and therefore reduce the number of mechanical components, but require motors with higher torque density and may increase motor mass, diameter, and

thermal loading. The choice between geared and direct-drive layouts is therefore not only an efficiency trade-off, but also a reliability, thermal, packaging, and certification trade-off.

The screw mechanism is also a decisive design element. Trapezoidal screws are simple and robust, and potentially self-locking, but relatively inefficient because of sliding friction and are generally less suitable for high-efficiency aerospace flight-control EMAs. Ball screws offer high efficiency and good positioning performance, but their load capacity, shock resistance, and degradation behavior depend strongly on ball–raceway contact conditions, preload, lubrication, contamination control, and load reversals. Planetary roller screws provide higher load capacity, stiffness, and lifetime, which makes them attractive for high-load aerospace applications [26,27]. However, their larger number of rolling contacts, tighter load-sharing requirements, and more complex kinematics increase the importance of lubrication, contact stress distribution, preload control, wear monitoring, and jamming prevention [28].

In safety-critical EMAs, the selection of the screw mechanism must therefore consider life prediction and failure progression, not only nominal efficiency and load capacity. Ball screws may degrade through ball–track contact fatigue, pitting, spalling, preload loss, lubricant degradation, contamination, backlash growth, increased friction torque, and ultimately seizure or jamming. Planetary roller screws may offer superior load capability and stiffness, but their degradation may involve roller–thread contact fatigue, lack of uniform load sharing, lubricant starvation, debris generation, preload variation, thread wear, bearing degradation, and thermal expansion effects. In both cases, progressive degradation can increase drive current, temperature, vibration, torque ripple, position error, and hysteresis before a critical loss of motion occurs.

A common way to express the fatigue life of rolling screw mechanisms is through an L10-type life estimate, which represents the number of revolutions or cycles that 90% of a population of identical components are expected to exceed under specified load and lubrication conditions. In simplified form, this life is related to the ratio between the dynamic load rating and the equivalent operating load, with an exponent that depends on the contact type and the assumptions adopted by the manufacturer or applicable standard. However, for aircraft EMAs, the direct use of catalogue L10 values is insufficient because the equivalent load depends on the actual mission profile, control-surface duty cycle, temperature, lubrication condition, vibration, shock loads, contamination, installation alignment, and degraded operating modes. Therefore, screw-life assessment for flight-control EMAs should be based on mission-profile-dependent load spectra, accelerated-life testing, tribological inspection, and condition-monitoring indicators such as friction torque, motor-current signatures, backlash evolution, vibration, temperature, and preload loss.

From a certification-oriented perspective, the key issue is not only the expected fatigue life of the screw, but also the detectability and controllability of degradation before it can evolve into a jammed load path. This is especially relevant for primary flight-control surfaces, where a jammed actuator can restrict or block the associated control surface. For this reason, mechanical transmission design should be coordinated with PHM, redundancy allocation, load-path architecture, inspection intervals, and jam-tolerant design measures. Recent flight-control EMA transmission developments also emphasize that screw selection, lubrication strategy, anti-rotation devices, sensor integration, and compact packaging must be considered together when designing mechanical transmissions for primary-control applications [29].

Table 3 summarizes representative degradation and failure mechanisms of screw-based EMA transmissions, together with observable indicators and design or monitoring implications.

Table 3. Representative degradation and failure mechanisms of screw-based EMA transmissions.

Mechanism	Typical Physical Origin	Observable Indicators	Possible Consequence	Design/Monitoring Implication
Contact fatigue	Repeated Hertzian contact stress in balls/rollers and raceways	Vibration increase, debris, noise, torque ripple	Pitting, spalling, loss of smooth motion	Mission-based L10 assessment, material selection, surface treatment, debris monitoring
Lubrication degradation	Thermal cycling, lubricant aging, contamination, lubricant starvation	Increased friction torque, temperature rise, current increase	Wear acceleration, seizure risk	Lubricant selection, sealing, thermal control, friction/current monitoring
Preload loss	Wear, elastic relaxation, thermal expansion, assembly tolerances	Backlash growth, positioning error, vibration	Reduced stiffness and accuracy	Preload monitoring, backlash estimation, maintenance thresholds
Backlash and wear	Repeated load reversals, inadequate lubrication, gear/screw wear	Position mismatch, hysteresis, degraded control accuracy	Limit-cycle behavior, force fighting, degraded surface control	Mechanical compensation, control adaptation, PHM thresholds
Bearing degradation	Rolling contact fatigue, contamination, misalignment	Vibration, heat, acoustic emission	Increased torque, misalignment, seizure	Bearing health monitoring, redundant support strategy
Contamination	Particles, internally generated wear debris, degraded seals	Torque spikes, irregular motion, debris detection	Local damage, jamming	Sealing, filtration, debris-tolerant design
Thermal expansion	Local heat concentration in screw, nut, bearings, housing	Clearance variation, preload change, friction increase	Binding, increased wear, loss of accuracy	Electro-thermal co-design, material matching, thermal validation
Structural misalignment	Installation tolerances, airframe deformation, load-path distortion	Side loads, nonuniform wear, current asymmetry	Accelerated wear, binding, jamming	Alignment-tolerant design, flexible couplings, load-path monitoring
Shock/overload	Gust loads, hard maneuvers, abnormal surface loads	Load peaks, torque peaks, permanent deformation	Brinelling, thread damage, loss of motion	Overload protection, torque limiting, structural margins
Progressive jamming	Combination of wear, debris, lubrication failure, thermal growth, or mechanical damage	Rapid increase in drive current, position tracking error, temperature rise, vibration	Blocked actuator or blocked control surface	Jam detection, disconnect mechanisms, redundant load paths, surface-level reconfiguration

Note: The mechanisms and indicators listed in the table are representative rather than exhaustive. Their relevance depends on screw type, load spectrum, lubrication condition, installation alignment, thermal environment, contamination control, duty cycle, and maintenance strategy. Observable indicators should therefore be interpreted together with actuator operating conditions and validated PHM thresholds.

Figure 3 summarizes the main mechanical transmission options used in flight-control EMAs, distinguishing between geared-drive and direct-drive architectures and the principal screw-based mechanisms used for the conversion of rotary to linear motion. The figure also highlights that transmission selection should be evaluated together with degradation monitoring and jam-tolerant design, rather than as a purely mechanical efficiency choice.

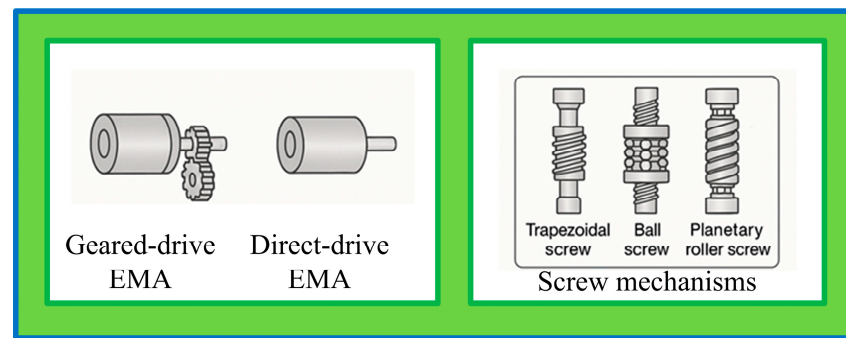


Figure 3. Main mechanical transmission options for flight-control electromechanical actuators (EMAs). The figure distinguishes geared-drive and direct-drive architectures and summarizes representative screw-based rotary-to-linear conversion mechanisms, including trapezoidal screws, ball screws, and planetary roller screws. Transmission selection should be assessed jointly with efficiency, stiffness, degradation monitoring, lubrication, thermal behavior, and jam-tolerant design.

Therefore, from a design perspective, mechanical transmission must be selected not only for efficiency, stiffness, and compactness but also for predictable degradation, monitorability, thermal robustness, and failure behavior. Jamming, backlash growth, wear, and lubrication degradation are discussed further in Section 6, where their safety implications and mitigation strategies are treated as part of the fault-tolerant EMA architecture.

4.3. Electric Motors

The electric motor is the core electromechanical conversion element of an EMA. Its selection is driven by the torque density, efficiency, dynamic response, thermal behavior, reliability, fault tolerance, controllability, and compatibility with the selected transmission. Several motor technologies have been considered for aircraft EMAs, including permanent-magnet synchronous motors (PMSMs), brushless DC (BLDC) motors, brushless AC motors, switched reluctance motors (SRMs), induction motors, and electrically excited synchronous machines and multiphase or modular fault-tolerant machines [10,11,19,30].

PMSMs and BLDC motors are the most common option in high-performance aerospace EMAs because they offer high efficiency, high power density, compactness, and precise torque control. These characteristics are well suited to flight-control actuators, where fast dynamic response, low mass, and accurate position tracking are required. However, permanent-magnet machines also introduce specific design limitations, including sensitivity to high temperature, risk of partial demagnetization, dependence on rare-earth materials, short-circuit fault consequences, and the need for robust power electronics and control algorithms [19,30]. These limitations become especially relevant in compact wing or tail installations, where cooling capability is limited and repeated transient loads may accelerate thermal aging.

SRMs are attractive from a fault-tolerance and thermal-robustness perspective because of their simple rotor structure, absence of permanent magnets, high-temperature capability, and tolerance to certain winding or converter faults. Their main drawbacks are higher torque ripple, acoustic noise, nonlinear magnetic behavior, and more complex control requirements. These characteristics can be problematic for precision flight-control actuation unless advanced control and torque-ripple mitigation strategies are applied. Induction machines are robust and do not rely on permanent magnets, but they generally provide lower torque density and efficiency than PMSMs in compact high-performance EMA applications, particularly when high dynamic response and limited installation volume are required. Electrically excited synchronous machines avoid permanent magnets but require excitation hardware, which increases complexity and may reduce power density.

The suitability of each motor technology therefore depends on the surface type, load level, duty cycle, cooling concept, redundancy architecture, and acceptable failure behavior. PMSM-based drives are generally favorable for compact and high-performance EMAs, especially when efficiency and torque density dominate. SRMs become more attractive when thermal robustness, magnet-free construction, and fault tolerance are prioritized, but at the cost of torque ripple and control complexity. Induction machines may be relevant for robustness-oriented applications, although their mass and efficiency penalties can be limiting in highly integrated aerospace actuators. Table 4 summarizes the main trade-offs among representative motor technologies for aircraft EMAs.

Table 4. Comparative suitability of electric motor technologies for flight-control EMAs.

Motor Technology	Main Advantages	Main Limitations	Suitability for EMAs
PMSM	High torque density, high efficiency, precise torque control, compactness	Magnet temperature sensitivity, demagnetization risk, rare-earth dependence, short-circuit fault consequences	Highly suitable for compact, high-performance EMAs when thermal and fault-tolerant design are properly addressed
BLDC/brushless AC	Compact, electronically commutated, mature drive technology	Torque ripple depending on design/control, converter dependence, thermal sensitivity	Suitable for many EMA applications, especially where mature control and compactness are required
SRM	Magnet-free rotor, high-temperature capability, fault tolerance, mechanical robustness	Torque ripple, acoustic noise, nonlinear control, lower torque smoothness	Promising for fault-tolerant or harsh-environment EMAs, but requires advanced control and ripple mitigation
Induction machine	Robust, magnet-free, mature technology	Lower torque density, rotor losses, reduced efficiency in compact high-dynamic applications	Possible in robustness-oriented designs, but less attractive where mass and efficiency dominate
Electrically excited synchronous machine	Magnet-free, controllable excitation	Excitation losses, additional hardware, increased complexity	Potential alternative where rare-earth avoidance is important, but packaging and efficiency must be justified
Multiphase/modular machines	Fault-tolerant operation, current redistribution, degraded-mode capability	More complex converter, control, sensing, thermal coupling, certification effort	Attractive for safety-critical EMAs requiring continued operation after selected electrical faults

Note: The suitability assessment is qualitative and application-dependent. Actual motor selection depends on actuator force and speed requirements, installation envelope, cooling concept, duty cycle, redundancy architecture, converter topology, fault-tolerance strategy, and certification assumptions.

Motor winding configuration is another important design variable. Concentrated windings can reduce end-winding length, improve manufacturability, and increase fault isolation between phases or modules. They are attractive for compact and modular actuator drives, but may increase space harmonics, torque ripple, and local losses. Distributed windings generally provide better sinusoidal magnetomotive force distribution, lower harmonic content, and smoother torque production, but may increase end-winding length and reduce phase isolation. For safety-critical EMAs, the winding layout must therefore be selected together with the fault-tolerance strategy, thermal design, insulation system, and converter topology.

Dual three-phase, multiphase, and modular winding configurations are particularly relevant for fault-tolerant EMA applications. By increasing the number of electrical phases or separating the machine into partially independent modules, these machines can continue operating after selected open-circuit, short-circuit, or converter faults [30–33]. In degraded

operation, healthy phases can redistribute current to maintain partial torque production and preserve limited actuator functionality. However, this benefit is not free: multiphase operation increases the number of power switches, current sensors, control loops, protection functions, thermal interactions, and certification evidence required. In addition, current redistribution after a fault may create local hot spots and accelerate insulation aging, so electro-thermal validation is required for both nominal and degraded modes.

Efficiency behavior must also be interpreted across the full operating envelope rather than at a single nominal point. Flight-control EMAs typically operate with intermittent duty cycles: long periods of low activity or small corrections are combined with short-duration peak loads during take-off, landing, maneuvers, gust rejection, or emergency operation. A motor-drive combination that is efficient at rated torque and speed may not be optimal at low-speed/high-torque, high-speed/low-torque, or repeated transient operating points. Therefore, efficiency maps, loss separation, and mission-profile-based operating distributions are more informative than isolated peak-efficiency values. For EMA design, relevant losses include copper losses, iron losses, inverter losses, bearing and windage losses, gearbox/screw friction, and additional losses associated with fault-tolerant redundancy or current redistribution.

Motor sizing in flight-control EMAs cannot be based only on nominal power. The maximum torque capacity, peak current, acceleration requirement, rotor inertia, thermal time constants, cooling capacity, duty cycle, and degraded-mode requirements must be considered in the early design phase [30,31]. This is especially important for primary flight-control actuators, where the motor may be required to sustain controlled operation under faulted or thermally constrained conditions. Consequently, motor design must be coordinated with the mechanical transmission, power electronics, control architecture, thermal path, PHM strategy, and certification assumptions. In this context, the benefits of multiphase machines depend not only on the motor topology, but also on the availability of suitable current-control strategies capable of exploiting their additional degrees of freedom. Finite-control-set model predictive control, adaptive cost functions, weighted stator-current tracking, and model-reference adaptive predictive current-control methods have been investigated for six-phase induction machines and related multiphase drives, showing their potential to improve current sharing, dynamic response, harmonic management, and control flexibility [34–36]. Although these approaches have not been developed specifically for aircraft EMAs, they provide a relevant control-design background for multiphase actuator drives intended for fault-tolerant or degraded-mode operation.

Overall, no motor technology is universally optimal for flight-control EMAs. PMSMs currently offer the strongest combination of torque density, efficiency, and control maturity, but require careful thermal and fault management. SRMs and magnet-free alternatives may improve robustness and reduce permanent-magnet dependence, but introduce control and torque-quality challenges. Multiphase and modular machines are promising for safety-critical EMAs because they support degraded operation, but they increase converter, thermal, sensing, and certification complexity. The final selection must therefore be made at the actuator-system level, considering the mission profile, surface criticality, redundancy concept, thermal feasibility, and acceptable degraded behavior.

4.4. Power Electronics and Control

Power electronics is essential for EMA operation because it regulates the voltage and current supplied to the motor and allows precise torque, speed, and position control. A typical EMA drive includes input filtering, a DC-link, inverter stages, gate drivers, sensors, protection circuits, and communication interfaces with the actuator control electronics or flight-control computer. At the actuator-control-unit level, mixed-signal interfaces and

signal-processing techniques are required to connect digital control functions with analog sensing, command-generation, and monitoring circuits. High-speed data-converter architectures based on sigma-delta modulation and time interleaving, together with over-sampling and noise-shaping techniques for speed estimation, illustrate enabling approaches for compact, high-resolution, and high-speed embedded control electronics [37–39].

The converter topology strongly affects EMA efficiency, power density, fault behavior, thermal loading, electromagnetic compatibility, and certification complexity. The most common solution is the two-level voltage-source inverter, which is simple, mature, and compatible with conventional three-phase motor drives. However, two-level inverters may impose high voltage slew rates, higher filter requirements, and increased insulation stress when used with high-voltage DC buses and wide-bandgap devices. Three-level topologies, such as neutral-point-clamped or T-type inverters, can reduce voltage stress, improve output waveform quality, and decrease electromagnetic emissions, but they require additional switches, gate drivers, voltage-balancing control, and protection functions. Matrix converters and direct AC–AC conversion concepts can reduce or eliminate bulky DC-link capacitors, but they introduce more complex modulation, protection, and bidirectional-switch requirements. For safety-critical EMAs, the selection of converter topology must therefore consider not only nominal efficiency but also fault isolation, thermal impedance, EMI/EMC, maintainability, and certification evidence. These trade-offs are summarized in Table 5, which compares representative converter topologies for EMA motor drives in terms of their main advantages, limitations, and relevance to aircraft flight-control applications.

Table 5. Representative power-converter topologies for EMA motor drives.

Converter Topology	Main Advantages	Main Limitations	Relevance for Aircraft EMAs
Two-level voltage-source inverter	Simple, mature, high control bandwidth, established protection methods	High dv/dt , higher EMI, higher insulation stress, possible need for filtering	Baseline solution for compact EMA drives; attractive when maturity and simplicity dominate
Three-level NPC/T-type inverter	Lower voltage stress, improved waveform quality, reduced dv/dt and EMI, potentially lower switching losses	More switches, more gate drivers, voltage-balancing control, increased protection complexity	Attractive for high-voltage EMA drives where EMI/insulation stress and efficiency are critical
Multiphase inverter	Supports fault-tolerant machines, current redistribution, degraded operation	Increased number of switches, sensors, control loops, and thermal interactions	Relevant for safety-critical EMAs requiring continued operation after selected electrical faults
Redundant inverter channels	Provides electrical redundancy and fault isolation	Higher mass, volume, cost, thermal load, and certification effort	Suitable for primary flight-control EMAs when actuator availability dominates
Matrix converter/direct AC-AC converter	Potential reduction in DC-link energy-storage components, bidirectional power flow	Complex modulation, protection, commutation, and filtering requirements	Potential interest for future integrated drives, but less mature for safety-critical EMA applications
Integrated motor drive	Reduces cable length, improves packaging, may reduce conducted emissions between converter and motor	Local heat concentration, maintenance difficulty, EMI coupling with sensors, qualification complexity	Promising for compact distributed actuation if thermal and EMC design are addressed

Note: The converter topologies listed are representative rather than exhaustive. Their relevance for aircraft EMAs depends on voltage level, power rating, motor type, switching technology, redundancy concept, thermal path, EMI/EMC constraints, protection strategy, and certification requirements.

Wide-bandgap semiconductor devices, such as SiC and GaN, are increasingly relevant for aerospace power converters because they can reduce losses, increase switching frequency, and improve power density [21,40]. These characteristics are attractive for compact EMAs, where mass and volume are critical. However, their advantages are accompanied by design challenges. Higher switching speeds increase dv/dt and di/dt , which can intensify conducted and radiated EMI, common-mode currents, insulation stress, bearing currents, and voltage overshoot at motor terminals [41]. In addition, the high power density enabled by wide-bandgap devices can concentrate heat in smaller packages, making junction-to-case, case-to-heatsink, and heatsink-to-structure thermal impedances critical design parameters.

Thermal impedance is therefore a key metric for EMA power electronics. The relevant thermal path includes semiconductor junctions, die attach, substrate, baseplate, thermal interface material, housing, structural attachment, and local cooling medium. Low conduction and switching losses are not sufficient if heat cannot be rejected through the available installation envelope. Repeated transient operation, fault-tolerant current redistribution, regenerative events, and degraded cooling conditions can produce thermal cycling and accelerate solder fatigue, bond-wire degradation, substrate cracking, capacitor aging, and gate-driver stress. For this reason, power-electronics design must be coordinated with thermal management, derating strategy, protection logic, and PHM.

Losses in EMA power electronics are strongly operating-point dependent. At low torque and low speed, control electronics, sensing, gate-drive power, and standby losses can become relatively important. At high torque, conduction losses in semiconductor devices and copper losses in the motor dominate. At high speed or high switching frequency, switching losses, magnetic losses, and filter losses become more relevant. During transient maneuvers, current peaks can increase semiconductor junction temperature and DC-link stress. During regenerative operation, the converter and DC-link must manage reverse power flow without overvoltage, instability, or power-quality problems. Therefore, converter efficiency should be assessed across representative operating points rather than through a single peak-efficiency value.

In MEA architectures, power electronics contribute directly to power-on-demand operation and distributed actuation. They also provide valuable signals for monitoring, since motor currents, voltages, switching states, DC-link variables, and temperature measurements can reveal abnormal behavior in both electrical and mechanical components. For example, changes in current signatures may indicate increased friction, load asymmetry, bearing degradation, or incipient jamming. Conversely, converter faults such as switch open-circuit, short-circuit, gate-driver malfunction, DC-link capacitor aging, sensor offset, or overvoltage can directly affect actuator availability and must be detected and isolated within the safety requirements of the flight-control system.

Electromagnetic compatibility is especially important in aircraft EMAs because high-power-density motor drives are located close to sensors, communication lines, flight-control computers, and other safety-critical equipment. The trend towards integrated motor drives and compact converters can reduce cable length and improve power density, but it can also intensify conducted and radiated EMI if the converter, motor, harness, and enclosure are not co-designed [41]. Therefore, power electronics design for EMAs must consider not only efficiency and mass, but also reliability, insulation coordination, electromagnetic compatibility, and maintainability.

Control architectures typically include nested current, speed, and position loops. For permanent-magnet machines, field-oriented control is commonly used to achieve accurate torque regulation. In redundant or multi-actuator configurations, additional control strategies may be required to avoid force fighting, synchronize actuator motion,

and ensure smooth reconfiguration after faults [42]. In addition, fast finite-state predictive current-control strategies can support real-time implementation of advanced motor-control algorithms by reducing computational burden while preserving the dynamic response required by high-performance electric drives [43].

Beyond conventional field-oriented and predictive control, robust and constraint-aware control methods are relevant for EMA drives subjected to load disturbances, current limits, speed limits, thermal constraints, and degraded operating conditions. Continuous terminal sliding mode control, nonsingular terminal sliding mode control, disturbance-observer-based methods, and control-barrier-function approaches have been investigated for PMSM servo systems to improve disturbance rejection while explicitly considering speed and current constraints [44,45]. Although these methods have generally been developed for PMSM servo drives rather than specifically for certifiable aircraft EMAs, they are relevant because flight-control actuators must maintain tracking performance under aerodynamic load disturbances, current saturation, thermal limits, and faulted conditions.

Current-constrained and voltage-tracking control methods are also relevant for DC-DC conversion stages that may appear in EMA power-conditioning units, local DC buses, or actuator-level power interfaces. Robust control of buck or bidirectional DC-DC converters under multi-source disturbances can help preserve DC-link stability, limit inductor or semiconductor current, and improve voltage regulation [46]. In aircraft actuation systems, these functions are important because actuator current peaks, regenerative operation, and bus-voltage transients can interact with the aircraft electrical network. Therefore, converter-level control should be considered together with motor-drive control, protection logic, power-quality requirements, and aircraft-level electrical stability.

The integration of power electronics and control is also central to fault-tolerant EMA design. Redundant inverter legs, dual electronic control units, multiphase drives, reconfigurable control laws, and fault isolation strategies can improve actuator availability, but introduce trade-offs in mass, volume, cost, thermal loading, and certification complexity [30–32,42]. These trade-offs are particularly important for primary flight-control surfaces, where both failure probability and failure consequences must be minimized.

4.5. Mass, Integration, and Thermal Constraints

The potential mass benefit of EMAs must be assessed at the aircraft level rather than only at the actuator level. A single EMA may be heavier than an equivalent hydraulic actuator because it integrates the motor, power electronics, sensors, transmission, housing, and thermal path. At the system level, however, EMAs can reduce or eliminate hydraulic pumps, reservoirs, pipes, valves, filters, fluid, and related maintenance requirements [10,11]. The net benefit therefore depends on the number of actuators, redundancy strategy, cooling concept, and electrical power-distribution architecture.

Recent model-based design studies for primary flight-control EMAs confirm this point, showing that preliminary actuator sizing must combine multi-domain simulation, component scaling laws, control requirements, mass estimation, and performance constraints rather than relying on actuator-force requirements alone [47].

Thermal integration is a major constraint because EMA losses are concentrated locally in windings, magnetic materials, power modules, bearings, gears, screw contacts, and structural interfaces. Unlike hydraulic systems, EMAs do not use circulating fluid as an inherent heat-transport mechanism; heat must be rejected through the actuator housing, structural conduction paths, local cooling interfaces, or surrounding airflow [48,49].

Temperature affects all main EMA domains. It increases winding resistance, can reduce permanent-magnet performance, accelerates semiconductor and capacitor aging, modifies lubricant properties, changes clearances, and can contribute to friction growth

or seizures [21,26,28]. Therefore, thermal design is directly linked to efficiency, reliability, fault tolerance, and PHM.

Distributed EMAs also interact dynamically with the aircraft electrical network. Rapid torque demands can produce current peaks and voltage transients, while some operating points may regenerate power into the DC link or distribution system [50]. Therefore, EMA integration requires a coordinated design of actuator, converter, thermal path, electrical grid, and power supply through a coupled electrical management strategy.

5. Energy-Efficiency Trade-Offs in Aircraft Actuation

Energy efficiency is one of the main motivations for electrified aircraft actuation, but it must be evaluated at the aircraft level rather than through isolated actuator efficiencies. The relevant energy path includes power generation and distribution, conversion stages, motor and transmission losses, load profile, thermal dissipation, redundancy overhead, and possible regenerated energy. Consequently, improvements at the actuator level do not necessarily translate into aircraft-level gains unless the associated impacts on thermal management, redundancy, and electrical-network interactions are considered.

Hence, replacing hydraulics with EMAs changes both the magnitude and location of losses. Centralized hydraulic losses are reduced or eliminated, but electrical, magnetic, mechanical, thermal, and protection-related losses are concentrated in distributed actuator units. The following subsections analyze these trade-offs for the SHA, EHA, EBHA, and EMA architectures [1,2,6–11,24,51].

5.1. Power-on-Demand Operation

Power-on-demand operation is the main energy-efficiency argument for electrified actuation. In SHA-based architectures, the hydraulic network must remain pressurized regardless of whether a specific actuator is moving, which generates continuous pump, leakage-compensation, pressure-regulation, circulation, and servo valve throttling losses [4–6].

EHAs and EMAs reduce this standby penalty because power is drawn mainly when actuation is required. EHAs generate hydraulic power locally through an electric motor-pump unit, whereas EMAs remove the hydraulic stage and directly convert electrical power into mechanical motion through the motor, converter, and transmission [6,8–11].

The resulting benefit depends on mission and surface utilization. Cruise corrections, take-off and landing operations, gust-load alleviation, maneuvers, and emergency modes impose very different duty cycles. Therefore, power-on-demand should be treated as an efficiency enabler whose value must be quantified in representative load profiles, including the energy consumed by sensors, control electronics, monitoring functions, thermal management, and redundancy [52,53].

5.2. Hydraulic Losses Versus Electrical Losses

Hydraulic and electromechanical actuation technologies differ not only in the magnitude of their losses, but also in where and when those losses occur. Centralized hydraulic systems exhibit pump inefficiencies, pipe pressure drops, leakage, fluid friction, pressure regulation, circulation losses, and servo valve throttling. A relevant characteristic of conventional hydraulic architectures is that part of these losses is associated with maintaining system availability and may occur even when a specific actuator is not actively moving [4–6]. Therefore, the energy penalty of hydraulic actuation is not determined only by the instantaneous mechanical work delivered to a control surface, but also by the standby and distribution losses required to keep the hydraulic network pressurized.

EMAs eliminate centralized hydraulic losses, but introduce conduction and switching losses in converters, copper and iron losses in machines, filter and cable losses, bearing and

gearbox losses, screw-mechanism friction, and auxiliary consumption from sensors, control electronics, monitoring functions, and redundant channels [10,11,21,51]. These losses are more closely tied to actuation demand than in centralized hydraulic systems, but they are concentrated in compact actuator units. This local concentration increases thermal stress and may require cooling provisions whose mass, volume, and power penalties must be considered at aircraft level.

EHAs and EBHAs combine both loss families. EHAs avoid much of the centralized hydraulic network but retain local pump, fluid, seal, and valve losses. EBHAs provide backup capability, but typically operate through the hydraulic path during normal operation, so their improvement in efficiency is secondary to their redundancy value [8,9,24]. Consequently, the transition from SHA to EHA, EBHA, or EMA should not be interpreted as a simple replacement of hydraulic losses by electrical losses, but as a redistribution of losses across the aircraft and across the mission profile.

The dominant loss mechanisms also vary strongly with operating point. At standby or very low actuation demand, centralized hydraulic systems may continue to consume power to maintain pressure, whereas EMAs mainly consume auxiliary power in sensors, control electronics, monitoring circuits, and communication interfaces. At low-speed/high-torque operation, motor copper losses, semiconductor conduction losses, and mechanical friction become dominant. At high-speed or high-switching-frequency operation, switching losses, magnetic losses, filter losses, and bearing/windage losses become more relevant. During short-duration peak maneuvers or gust-rejection events, current peaks can increase semiconductor junction temperature, winding temperature, and DC-link stress. During regenerative operation, aerodynamic loads or actuator deceleration may drive the motor as a generator, and the DC-link must absorb, redistribute, store, or dissipate the returned energy without overvoltage or power-quality problems [50].

For this reason, a fair comparison between SHAs, EHAs, EBHAs, and EMAs requires representative mission profiles and control-surface load histories. Published actuator-level efficiencies, converter efficiencies, force densities, and mass estimates are useful, but they cannot be generalized without specifying aircraft class, control-surface type, duty cycle, load spectrum, thermal boundary conditions, redundancy requirements, and installation constraints. In this review, qualitative comparisons are therefore interpreted as relative technology-level tendencies, while representative numerical examples from the literature are included where they are available and comparable.

A representative mission-level example is provided by Fu et al. [53], who developed a 6 DOF flight-dynamics-based simulation framework to estimate the power consumption of flight-control surface EMAs. Their case study, based on a small all-electric aircraft, showed that EMA energy consumption is strongly mission-dependent: it increases with more aggressive control gains, grows approximately linearly with turbulence intensity, and increases as the trajectory radius decreases. In a waypoint fly-over maneuver, the reported EMA energy at the same waypoint increased from 146.33 J for a 115 m turning radius to 177.02 J for a 90 m radius and 249.39 J for a 70 m radius. The corresponding propulsive energy values were 1034.59 kJ, 1057.31 kJ, and 1123.88 kJ, respectively [53].

This example illustrates two important points. First, in this aircraft class and mission segment, flight-control EMA energy is several orders of magnitude smaller than propulsion energy. Second, actuator energy is not negligible from a system-design perspective because it changes significantly with trajectory aggressiveness, control activity, and flight condition. In the example above, reducing the turning radius from 115 m to 70 m increased the EMA energy at the waypoint by approximately 70%, even though the absolute EMA energy remained small compared with propulsion energy. Such results support the need for mission-level EMA

energy assessment when sizing actuator drives, local power electronics, secondary power supplies, emergency backup energy, and thermal-management provisions.

To make this mission-level effect more explicit, Table 6 summarizes the numerical values reported by Fu et al. [53] for the waypoint comparison under three different turning-radius conditions. The table is not intended as a general scaling law for all aircraft, but as a representative example showing how trajectory requirements and control activity can affect EMA energy demand within a given mission scenario.

Table 6. Representative mission-level EMA energy example adapted from Fu et al. [53].

Case	Turning Radius	EMA Energy at WP1	Propulsive Energy at WP1	Design Interpretation
Smoothest turn	115 m	146.33 J	1034.59 kJ	Lower control activity and lower induced-drag penalty
Intermediate turn	90 m	177.02 J	1057.31 kJ	Moderate increase in EMA and propulsive energy
Tightest turn	70 m	249.39 J	1123.88 kJ	Higher control activity, higher bank angle, higher induced drag, and higher EMA energy

The values in Table 6 are aircraft- and mission-specific and should not be generalized to other aircraft classes without rescaling the actuator, aerodynamic model, control laws, duty cycle, and thermal assumptions. Nevertheless, they provide a useful numerical illustration of why actuator energy efficiency must be evaluated at mission level rather than only through isolated component efficiencies.

5.3. Weight, Volume, and Power-Density Trade-Offs

Aircraft-level efficiency is strongly coupled to mass, volume, and power density. Hydraulic actuators can be compact on the surface because the supporting infrastructure is distributed elsewhere in the aircraft. Therefore, pumps, reservoirs, accumulators, valves, pipes, fluid, filters, heat exchangers, and maintenance access must be included in any fair comparison [4–6].

EMAs may simplify the architecture at the aircraft level, but the local actuator must include the motor, power electronics, sensors, transmission, control electronics, housing, and thermal path. Therefore, individual EMAs can be heavier or larger than equivalent hydraulic actuators even when the overall system becomes simpler [10,11,51]. EHAs and EBHAs occupy intermediate positions by reducing some hydraulic distribution while retaining local or backup hydraulic components [8,9,24].

The same trade-off appears inside the EMA. Geared architectures allow for compact high-speed motors, but add losses, backlash, wear, and failure modes. Direct-drive concepts reduce mechanical stages but require higher-torque motors. Ball screws provide high efficiency, whereas planetary roller screws improve stiffness and load capacity at the cost of greater mechanical complexity and stronger tribological requirements [10,26–28].

Thus, the most efficient solution is architecture- and mission-dependent. It depends on the actuator compactness, aircraft-level mass, force capability, cooling capacity, duty cycle, reliability, redundancy, maintenance, and certification maturity [54].

5.4. Thermal Management and Aircraft-Level Efficiency

Thermal management determines how much of the theoretical efficiency gain of EMAs can be realized in practice. Hydraulic systems distribute part of their heat through the fluid network and centralized thermal-management paths, whereas EMAs and EHAs concentrate losses in local motors, converters, bearings, gears, screw mechanisms, housings, and structural attachments [33,48,49,52]. This local heat concentration can limit continuous operation, reduce component lifetime, accelerate lubricant degradation, and require cooling

provisions whose mass, volume, maintenance burden, and power consumption must be included in the aircraft-level comparison.

In EMAs, the main heat sources are motor copper and iron losses, semiconductor conduction and switching losses, DC-link and filter losses, bearing losses, gearbox losses, screw-mechanism friction, brake or no-back-device losses, and auxiliary electronics. These heat sources are spatially concentrated and are often located in wing, tail, or control-surface regions with limited installation volume and restricted airflow. As a result, the thermal path from the heat source to the aircraft structure or surrounding air becomes a major design constraint. Relevant thermal resistances include winding-to-housing, semiconductor junction-to-case, case-to-heat-sink, thermal-interface-material resistance, housing-to-structure, and structure-to-ambient paths.

Several thermal-management strategies can be considered for EMA-based flight-control systems. Passive structural conduction uses the actuator housing, mounting points, and surrounding airframe structure as heat-spreading paths. This approach is attractive because it avoids pumps, fans, and additional moving parts, but it depends strongly on installation geometry, contact resistance, material selection, and the thermal boundary conditions of the airframe. Natural or forced air cooling can be useful when local airflow is available, but its effectiveness varies with altitude, flight phase, enclosure design, and contamination constraints. Forced air cooling improves heat-transfer capability compared with natural convection, but it may require fans, ducts, or dedicated airflow paths, adding power consumption, mass, noise, and maintenance requirements.

Liquid cooling can provide higher heat-transfer capability and more stable temperature control, but it introduces mass, pumps or fluid circuits, leakage concerns, maintenance requirements, and integration complexity. Therefore, liquid cooling may be justified for high-power or highly integrated actuators, but it can partially offset the architectural simplicity expected from EMAs. Thermal interface materials (TIMs) and advanced packaging are also important because they affect the thermal resistance between power modules, motor windings, housings, and structural heat paths. Poor contact quality, assembly variability, aging, or vibration-induced degradation of TIMs can significantly increase temperature rise even when component losses are low.

Phase-change materials (PCMs) may help absorb short-duration thermal peaks associated with maneuvers, gust rejection, or emergency operation, but they do not eliminate the need to reject the stored heat over the mission. Their usefulness depends on duty cycle, latent-heat capacity, packaging mass, recharge time, qualification, and long-term stability under vibration and thermal cycling. PCMs are therefore more suitable as transient thermal buffers than as standalone cooling solutions.

Thermal design is directly linked to reliability and fault tolerance. High temperature increases winding resistance, reduces permanent-magnet margin, accelerates semiconductor and capacitor aging, modifies lubricant viscosity, changes mechanical clearances, and can contribute to friction growth or seizure [21,26,28]. In fault-tolerant motor drives, current redistribution after a phase or converter fault may create local hot spots in otherwise healthy windings or power modules. Similarly, redundant power-electronics channels and compact integrated motor drives can improve availability but also increase local thermal density. Consequently, thermal validation must consider not only nominal operation but also degraded modes, repeated transient loads, cooling degradation, and worst-case installation conditions.

Thermal management also affects aircraft-level energy efficiency. A highly efficient actuator at component level may lose part of its benefit if it requires heavy cooling hardware, continuous auxiliary cooling power, excessive thermal margins, or conservative derating. Conversely, an EMA with moderate local losses may be attractive if heat can be rejected through existing structural paths and if the mission profile is dominated by low-duty-cycle

operation. Therefore, the relevant metric is not instantaneous motor-drive efficiency alone, but mission-level performance including actuator losses, cooling-system penalties, mass effects, thermal derating, degradation, and maintenance intervals.

To summarize these trade-offs, Table 7 compares representative thermal-management strategies for EMA-based flight-control systems. The comparison is qualitative and design-oriented; the preferred solution depends on actuator power level, duty cycle, installation location, allowable temperature limits, redundancy architecture, maintainability, and certification evidence.

Table 7. Thermal-management strategies for EMA-based flight-control systems.

Thermal-Management Strategy	Main Advantages	Main Limitations	Suitability for Aircraft EMAs
Structural conduction through housing and airframe	Passive, simple, no moving parts, compatible with distributed actuation	Strongly dependent on installation geometry, contact resistance, material selection, and airframe thermal boundary conditions	Attractive for moderate-duty actuators when reliable structural heat paths are available
Natural air cooling	Low complexity, no auxiliary pumps or fans	Limited heat-transfer capability; depends on local airflow, altitude, enclosure, and contamination constraints	Useful for low-to-moderate-power actuators with favorable installation conditions
Forced air cooling	Improved heat transfer compared with natural convection	Requires fans, ducts, or dedicated airflow; adds power consumption, mass, noise, and maintenance	Possible for accessible installations, but less attractive in compact sealed actuator bays
Liquid cooling	High heat-transfer capability and stable temperature control	Adds fluid circuits, pumps, leakage risk, mass, maintenance, and integration complexity	Relevant for high-power or highly integrated EMAs if thermal demand justifies added complexity
Thermal interface materials	Reduces contact resistance between power modules, housings, and structural paths	Performance depends on assembly quality, aging, pressure, vibration, and thermal cycling	Important for compact power electronics and integrated motor drives
Phase-change materials	Absorbs short-duration thermal peaks and smooths transient temperature rise	Adds mass; requires heat rejection after melting; limited by duty cycle and recharge time	Potentially useful for intermittent peak loads, emergency operation, or highly transient duty cycles
Derating/duty-cycle management	Protects components from overheating and extends lifetime	Reduces available actuator performance under thermal constraints	Useful as a protection layer, but must be compatible with flight-control authority requirements
Integrated electro-thermal design	Optimizes motor, converter, housing, cooling path, and control strategy together	Requires coupled modeling, validation, and multidisciplinary design effort	Essential for high-performance or safety-critical EMAs

Note: The strategies listed are representative and may be combined in practical EMA designs. Their suitability depends on actuator location, heat-generation profile, available heat-rejection paths, ambient conditions, duty cycle, redundancy requirements, and aircraft-level integration constraints.

Overall, thermal management is not an auxiliary design issue but a central element of EMA architecture selection. It affects actuator sizing, power-electronics layout, motor selection, lubricant behavior, mechanical clearances, PHM thresholds, redundancy strategy, and certification evidence. For safety-critical applications, the thermal design must demonstrate that the actuator can satisfy its required performance not only under nominal operation, but also under representative transient loads, degraded cooling conditions, and fault-tolerant operating modes.

5.5. Comparison Between SHA, EHA, EBHA, and EMA

The preceding analysis shows that no actuation technology is universally optimal. Each concept represents a different compromise between energy efficiency, force density, system complexity, fault tolerance, thermal feasibility, maturity, and certification risk.

While Table 2 provided a general architectural comparison, Table 8 focuses on the energy-efficiency implications at the actuator and aircraft levels.

Table 8. Energy-efficiency design trade-offs of aircraft flight-control actuation technologies. The comparison is qualitative and design-oriented, with representative numerical examples discussed in the text where available.

Energy-Efficiency Aspect	SHA	EHA	EBHA	EMA
Dominant loss sources	Central hydraulic pump losses, pressure regulation, leakage, servovalve throttling, pipe pressure drops	Motor-pump losses, local hydraulic losses, converter losses, fluid heating	Hydraulic losses in normal operation; motor-pump losses in backup mode	Inverter losses, motor losses, gearbox/screw friction, bearing losses, local thermal losses
Standby/idling behavior	Hydraulic system remains pressurized, causing parasitic losses even with inactive actuators	Low standby losses; local hydraulic power generated only when required	Similar to SHA in normal hydraulic operation, with additional backup readiness requirements	Low standby losses, mainly from control electronics, sensors, and monitoring functions
Actuator-level vs. aircraft-level mass	Compact actuator, but heavy aircraft-level hydraulic infrastructure	Heavier local actuator, but reduced hydraulic distribution	High local complexity, but may reduce hydraulic-system redundancy	Potential aircraft-level simplification, but local actuator mass can increase due to motor, drive, sensors, and transmission
Thermal distribution	Heat distributed through hydraulic fluid and centralized thermal-management paths	Heat concentrated in local electro-hydraulic unit	Mixed thermal behavior from hydraulic and electrical subsystems	Heat concentrated in motor, power electronics, bearings, gearbox/screw, and housing
Mission/load-profile sensitivity	Efficiency affected by continuous hydraulic availability rather than individual actuator duty cycle	Efficiency improves for intermittent actuation but depends on pump/motor duty cycle	Efficiency benefit depends on how often backup mode is used and on hydraulic architecture	Strongly dependent on duty cycle, peak loads, control activity, gust response, and flight phase
Regenerated power potential	Not applicable	Limited or indirect	Limited	Possible during load-driven or deceleration phases, but requires DC-link and power-management strategy
Main energy-efficiency advantage	High force capability with mature centralized supply	Power-on-demand while retaining hydraulic force density	Redundancy and gradual electrification without full architectural disruption	Direct electrical-to-mechanical conversion, distributed actuation, no hydraulic infrastructure
Main energy-efficiency penalty	Continuous hydraulic infrastructure losses and maintenance burden	Local hydraulic complexity and thermal concentration	Limited efficiency gain during normal hydraulic operation	Local heat concentration, mass of drive/transmission, regenerated-power management, and redundancy requirements

Note: The qualitative comparison summarizes relative energy-efficiency tendencies among SHA, EHA, EBHA, and EMA technologies. The entries should not be interpreted as universal numerical values because actuator losses depend strongly on aircraft class, surface size, duty cycle, load spectrum, control activity, redundancy requirements, converter topology, and thermal boundary conditions.

SHAs remain attractive where force density, maturity, and proven certification dominate, but they suffer from aircraft-level hydraulic losses and maintenance burden. EHAs improve power-on-demand behavior and reduce distributed hydraulic infrastructure, while retaining local hydraulic components and thermal concentration. EBHAs mainly support redundancy and incremental electrification; their normal-operation efficiency benefit is

limited because they still rely on centralized hydraulics. EMAs provide the strongest route to distributed, fully electric actuation, but their advantages depend on solving local heat concentration, transmission reliability, regenerated-power handling, redundancy overhead, and certification.

Consequently, the energy-efficiency assessment in this section should be interpreted as architecture- and mission-dependent. Mixed architectures may remain optimal during the transition: secondary flight-control surfaces, trim systems, high-lift devices, and selected spoiler applications are natural candidates for progressive EMA deployment, whereas primary flight-control surfaces require stronger evidence of jamming mitigation, thermal robustness, redundancy management, PHM capability, and safe degraded operation [55].

EMA advantages are strongest when reductions in hydraulic infrastructure, power-on-demand operation, maintainability benefits, and distributed electrical integration outweigh penalties associated with local mass, thermal management, redundancy, regenerated-power handling, and certification evidence. Therefore, energy efficiency should not be interpreted as a purely electrical metric, but as part of an integrated aircraft-level design framework that jointly considers mission-level energy consumption, mass, thermal behavior, redundancy, fault tolerance, maintainability, certification requirements, and operational cost [53,54,56].

Figure 4 summarizes these trade-offs by providing a qualitative positioning of the main flight-control actuation technologies in terms of aircraft-level energy efficiency and fault-tolerance/certification maturity. The figure is not intended as a quantitative ranking, but rather as a conceptual synthesis of the system-level trends discussed in this section.

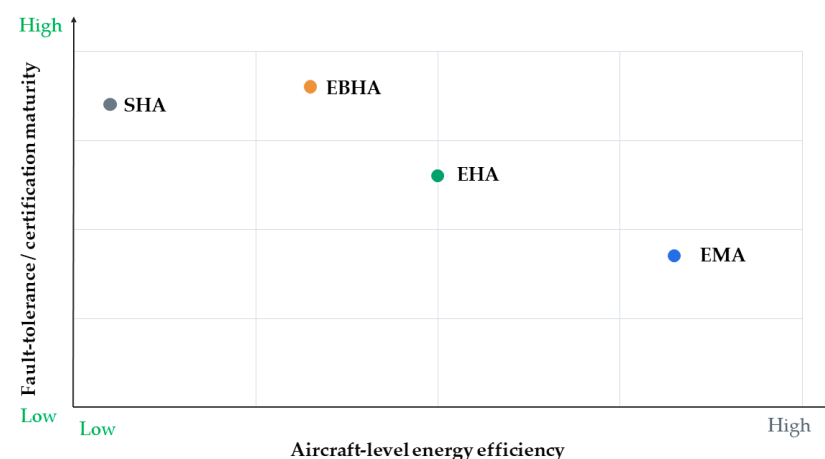


Figure 4. Qualitative positioning of SHA, EHA, EBHA, and EMA technologies in terms of energy efficiency and fault-tolerance/certification maturity. The figure is intended as a conceptual synthesis of the trade-offs discussed in Section 5, not as a quantitative ranking.

6. Fault Modes, Redundancy and Safety-Critical Design

EMAs change not only the energy source of flight-control actuation, but also the way failures originate, propagate, and must be mitigated. Unlike many hydraulic architectures, EMAs provide fewer inherent pressure-relief, bypass, or fluid-based load-redistribution mechanisms. As a result, faults in the mechanical transmission, motor drive, sensor chain, or control electronics can affect the load path more directly. Safety-critical EMA applications therefore require either a safe state or continued degraded operation, depending on surface criticality and aircraft-level control allocation [10–15,42,57,58].

This makes fault tolerance a multi-domain design problem that must be addressed from the earliest stages of architecture selection and co-designed across mechanical, electrical, sensing, thermal, software, and control domains. Section 6 therefore reviews representative EMA failure modes, mechanical jamming, electrical and power-electronics faults,

sensor and control faults, redundancy strategies, common-cause failures, force fighting, load-sharing issues, and fail-safe or fault-tolerant architectural approaches.

6.1. Failure Taxonomy of Aircraft EMAs

EMA failures can be classified according to the physical domain in which they originate: mechanical transmission, electric motor, power electronics, sensors, control electronics, software, communication links, and thermal or environmental stress. This classification reflects the multi-domain nature of EMAs and highlights the need for integrated reliability analysis across mechanical, electrical, thermal, and control subsystems [10,11,18,59]. Table 9 summarizes representative failure modes, possible effects, and mitigation strategies. It is intended as a design-oriented taxonomy rather than an exhaustive failure catalogue, since the severity of each failure mode depends on surface criticality, actuator architecture, redundancy level, and available control reconfiguration.

Table 9. Main failure modes, effects, and mitigation strategies in aircraft EMAs.

Failure Domain	Typical Failure Modes	Possible Effects	Mitigation Strategies
Mechanical transmission	Jamming, backlash, wear, lubrication loss, bearing faults, gear damage	Blocked surface, degraded positioning accuracy, friction increase, loss of motion	Jam-tolerant design, redundant load paths, disconnect mechanisms, condition monitoring
Electric motor	Winding short circuit, open phase, insulation degradation, demagnetization	Torque loss, torque ripple, overheating, degraded dynamic response	Multiphase machines, redundant windings, thermal protection, fault-tolerant control
Power electronics	Switch failure, gate-driver fault, DC-link capacitor aging, overvoltage, overcurrent	Loss of drive, uncontrolled current, converter shutdown, thermal overstress	Redundant inverter legs, protection circuits, derating, health monitoring
Sensors	Position sensor fault, current sensor offset, temperature sensor failure	Incorrect feedback, instability, undetected overload, degraded control accuracy	Sensor redundancy, analytical redundancy, voting, plausibility checks
Control and communication	Software error, communication loss, parameter mismatch, synchronization error	Incorrect command, degraded tracking, force fighting, unsafe reconfiguration	Independent control channels, monitoring logic, safe-state management
Thermal/environmental	Overheating, thermal cycling, vibration, contamination	Accelerated aging, insulation degradation, friction increase, lubricant deterioration	Integrated thermal design, environmental qualification, prognostics

Note: This taxonomy is design-oriented and not exhaustive. The severity and detectability of each failure mode depend on actuator architecture, surface criticality, redundancy level, monitoring capability, operating condition, and aircraft-level control allocation.

Approaches based on failure modes, effect, and criticality analysis (FMECA) are particularly useful in this context because they allow the severity, occurrence, and detectability of EMA failure modes to be considered jointly. Recent work has also explored fuzzy FMECA approaches for EMAs to reduce the subjectivity of conventional criticality ranking and to identify vulnerable components that require stronger mitigation measures [59].

6.2. Mechanical Jamming, Degradation, and Jam-Tolerant Design Strategies

Mechanical failures are among the most critical failure modes in flight-control EMAs because they can directly affect the mechanical load path between the motor and the aerodynamic surface. In linear flight-control EMAs, this load path often includes a gearbox and a screw-based mechanism exposed to cyclic loads, vibration, thermal variation, lubrication degradation, and high contact stresses [10,26–28]. For this reason, the mechanical transmission must be assessed not only in terms of nominal efficiency, compactness, stiffness,

and force capability, but also in terms of degradation progression, failure detectability, and post-fault controllability.

Mechanical jamming is the most severe form of mechanical failure. A blocked screw, nut, gearing, or bearing can immobilize the control surface and, depending on the criticality of the surface and the aircraft-level redundancy architecture, may lead to hazardous or catastrophic consequences [15,16,60]. Unlike many hydraulic architectures, where pressure relief, bypass paths, or fluid compliance may provide some inherent mitigation depending on the system design, a screw-based EMA can create a direct and rigid mechanical connection between the motor/transmission and the control surface. If this load path becomes blocked, simply removing electrical power from the motor may not be sufficient to restore surface mobility.

Jamming can originate from several degradation mechanisms, including screw or bearing seizure, lubricant loss, contamination, internally generated debris, gear damage, excessive preload variation, thermal expansion, structural misalignment, or overload-induced deformation. In many cases, jamming is not an isolated instantaneous event but the final stage of progressive degradation. Prior indicators may include increased friction torque, abnormal motor-current signatures, temperature rise, vibration, position-tracking error, backlash growth, torque ripple, or hysteresis. These symptoms are important for condition monitoring, but PHM alone cannot normally be considered a complete safety barrier unless its detection reliability, uncertainty bounds, false-alarm rate, missed-detection probability, and certification acceptability are demonstrated.

Backlash, wear, and lubrication degradation are particularly relevant because they can progressively reduce positioning accuracy and stiffness before producing a more severe mechanical failure. Backlash may appear because of screw or gearbox wear, preload loss, bearing degradation, thermal effects, or repeated load reversals. Its effects include degraded positioning accuracy, limit-cycle behavior, increased control effort, and, in multi-actuator surfaces, force fighting between redundant actuators. Lubrication degradation can increase friction, accelerate wear, modify thermal behavior, and increase the risk of seizure. These effects are strongly dependent on temperature, duty cycle, vibration, contamination, sealing, lubricant selection, and maintenance intervals.

Therefore, mechanical transmission design for flight-control EMAs must be approached from a failure-progression perspective. The key question is not only whether a screw, bearing, or gearbox can withstand the nominal load, but whether its degradation can be detected, isolated, tolerated, or mitigated before it compromises the control surface. This is especially important for primary flight controls, where a jammed surface may have aircraft-level controllability consequences. For secondary surfaces, high-lift devices, trim systems, or spoilers, the acceptable degraded modes may be less severe, but jamming still affects dispatch reliability, maintainability, and operational safety.

Several jam-tolerant or anti-jamming strategies have been proposed for EMA-based flight-control systems, including disconnect mechanisms, clutches, torque limiters, redundant load paths, load-path separation, differential transmission concepts, and surface-level redundancy. Disconnect mechanisms aim to mechanically isolate a jammed actuator from the control surface, allowing another actuator or another surface to retain control authority. Separation clutches can disengage the drive train from the load path, although they introduce additional wear, control logic, and failure modes. Torque limiters can prevent overload propagation and protect mechanical components, but they may not release a fully seized screw. Brakes and no-back devices can support load holding and prevent undesired back-driving, but they must also be assessed as possible sources of additional friction or jamming. Differential screw arrangements and redundant mechanical load paths can improve tolerance to selected internal failures, although they increase mass, packaging complexity, backlash management, and validation effort.

At the aircraft level, jamming can also be mitigated through multi-actuator surfaces, distributed control allocation, or surface-level redundancy. In these architectures, the failure of one actuator or one surface can be compensated by other actuators or aerodynamic surfaces. However, this approach requires reliable fault detection, safe disconnection or isolation, and careful management of force fighting and load sharing. Multiple actuators connected to the same surface may generate internal loads if their position commands, stiffness, sensor measurements, or dynamic responses are not sufficiently coordinated. Consequently, mechanical jam tolerance must be integrated with control architecture, redundancy allocation, structural design, PHM, and aircraft-level safety assessment.

Table 10 summarizes representative anti-jamming and jam-tolerant strategies for flight-control EMAs. The comparison is qualitative and design-oriented; the suitability of each strategy depends on surface criticality, load level, installation envelope, redundancy architecture, fault-detection capability, and certification evidence.

Overall, jamming mitigation cannot be addressed by a single component-level solution. A certifiable EMA architecture requires a combination of mechanical design, degradation monitoring, redundancy, fault isolation, safe disconnection or load-path reconfiguration, and aircraft-level control allocation. The appropriate solution depends strongly on whether the actuator is intended for a primary or secondary flight-control surface. For primary surfaces, jam tolerance and post-fault controllability must be demonstrated at the aircraft level, whereas for secondary surfaces the emphasis may be placed on safe isolation, dispatch reliability, and maintainability. This distinction is essential when assessing the readiness of EMAs for broader adoption in more-electric aircraft.

Table 10. Comparison of anti-jamming and jam-tolerant strategies for flight-control EMAs.

Strategy	Working Principle	Advantages	Limitations	Certification/Design Implications
Disconnect mechanism	Mechanically separates a jammed actuator from the control surface or load path.	Can restore surface mobility if another actuator or aerodynamic surface remains available.	Adds mass, complexity, sensing, actuation, and additional failure modes; must operate reliably under load.	Requires demonstration of reliable jam detection, release under representative loads, and safe post-disconnect behavior.
Separation clutch	Allows controlled engagement or disengagement between the drive train and the load.	Useful for isolating drive-side failures or enabling backup actuation.	The clutch can wear, slip, fail to engage, or fail to disengage; limited effectiveness if the jam occurs downstream.	Requires fail-safe clutch logic, wear monitoring, and validation under load reversals and thermal cycling.
Torque limiter	Limits transmitted torque when abnormal loads or overloads occur.	Protects gears, screws, bearings, and structural interfaces from excessive loads.	Does not necessarily release a fully seized screw; may reduce available control authority if activated.	Requires careful threshold selection to avoid nuisance activation or insufficient protection.
Brake/no-back device	Holds the load or prevents undesired back-driving under selected conditions.	Useful for load holding, surface stability, and protection against back-driving loads.	May itself become a jam source; can increase friction, thermal loading, and mechanical complexity.	Must be assessed both as a protection device and as a possible contributor to common-cause or mechanical failure.
Differential screw arrangement	Uses differential motion or alternative mechanical paths to preserve motion after selected internal failures.	Can improve jam tolerance and mechanical reconfiguration capability.	Mechanically complex; may increase mass, friction, backlash, and validation effort.	Requires detailed failure-mode analysis and proof that the mechanism does not introduce new critical jam conditions.
Redundant mechanical load path	Provides an alternative load path if one path fails or becomes degraded.	Can maintain limited actuation capability after selected failures.	Packaging, synchronization, inspection, and load sharing become more complex.	Requires load-path independence, monitoring, and common-cause failure assessment.

Table 10. *Cont.*

Strategy	Working Principle	Advantages	Limitations	Certification/Design Implications
Dual-actuator or multi-actuator surface	Uses more than one actuator to drive the same surface.	Allows continued operation if one actuator is disconnected, degraded, or unavailable.	Can generate force fighting, structural overload, control interaction, and common power/cooling dependencies.	Requires active or passive load sharing, force equalization, impedance coordination, and fault isolation.
Surface-level redundancy	Uses other aerodynamic surfaces or control-allocation laws to compensate for a jammed surface.	Reduces dependence on a single actuator or surface.	Compensation may be limited by flight condition, aerodynamic authority, and handling-quality requirements.	Requires aircraft-level controllability analysis and degraded-mode certification evidence.
PHM-based early detection	Detects degradation before it evolves into a jam using current, vibration, temperature, position error, or friction indicators.	Supports predictive maintenance and may reduce the probability of in-service jamming.	Usually advisory unless validated and accepted for safety credit; sensitive to false alarms and missed detections.	Requires representative degradation datasets, uncertainty management, and detection-performance validation.
Jam-tolerant mechanical architecture	Designs the transmission so that selected internal failures do not block the surface.	Can reduce the severity of mechanical failures and improve degraded-mode behavior.	Often increases mechanical complexity and may reduce efficiency or increase mass.	Requires fault-injection testing, degraded-mode validation, and maintainability assessment.

Note: The suitability of each anti-jamming or jam-tolerant strategy depends on control-surface criticality, actuator load level, installation envelope, redundancy architecture, fault-detection capability, and certification evidence. The table is intended to support design comparison and should not be interpreted as a universal ranking of mitigation effectiveness.

6.3. Electrical and Power-Electronics Faults

Electrical and power-electronics faults directly affect the ability of an EMA to generate and regulate torque. Motor faults such as winding short circuits, open-phase operation, insulation degradation, demagnetization, or harness failures can reduce torque capability, increase torque ripple, generate unbalanced currents, accelerate heating, or force actuator shutdown [13,14,30–33].

Power electronics introduce additional failure modes. Semiconductor switches may fail open or short, gate drivers may malfunction, DC-link capacitors may age, and protection circuits may cause shutdown under overcurrent, overvoltage, or over-temperature conditions. These failures can lead to loss of drive capability, uncontrolled current, excessive DC-link voltage, electromagnetic disturbances, or loss of actuator availability [21,41,42].

The use of high-voltage DC networks and high-power-density converters in MEA architectures makes reliable motor-drive design a central element of EMA safety. Wide-bandgap devices can improve efficiency and power density, but their fast switching transitions can intensify electromagnetic interference, insulation stress, and filtering requirements [9,21,41]. Electrical redundancy can be introduced through multiphase machines, dual three-phase windings, redundant inverter legs, independent power supplies, or modular motor-drive architectures, although these solutions increase mass, thermal coupling, control complexity, and certification effort [14,30,32,42].

6.4. Sensor, Control, and Communication Faults

Accurate sensing and robust control are essential for EMA operation. EMAs rely on position, speed, current, voltage, force or torque, temperature, and sometimes vibration measurements to close control loops, protect the actuator, and support safe reconfiguration. Faults in these measurements can compromise both nominal performance and degraded-mode operation [17,18,22,61].

Position-feedback faults are especially critical because the actuator control unit uses position information to track commanded surface deflection. Faults in resolvers, encoders, RVDTs, or LVDTs may produce incorrect feedback, loss of synchronization, biased position estimates, or intermittent measurement loss. Current-sensor faults can compromise torque control and protection logic, while temperature-sensor faults can prevent the detection of thermal overload [13,14,18].

Control failures may arise from software errors, parameter mismatch, communication failures, timing errors, or incorrect reconfiguration logic. In redundant systems, the control problem becomes more complex because multiple channels may interact through the same mechanical load. Without appropriate coordination, redundant actuators can generate opposing forces, leading to force fight, increased structural loads, additional energy consumption, and accelerated degradation [12,14,42].

For this reason, safety-critical EMA control must include not only nominal tracking loops, but also monitoring logic, plausibility checks, voting strategies, fault isolation, safe-state management, and reconfiguration rules. These functions must be designed to avoid single points of failure and ensure that a fault in one sensing or control channel does not propagate to unsafe actuator behavior [57,58].

6.5. Redundancy Levels and Architectural Strategies

Redundancy is a key design principle for safety-critical flight-control actuation. In EMAs, redundancy can be implemented at several levels, each with different implications for mass, complexity, fault coverage, thermal behavior, and certification [12–14,42,57].

At the control-surface level, multiple actuators can be connected to the same surface. At the actuator level, dual or parallel EMAs can provide redundant load paths. At the motor level, dual motors, torque-summed configurations, speed-summed configurations, or multiphase machines can improve availability. At the converter and sensor levels, redundant inverter legs, multiple sensing channels, voting logic, and analytical redundancy can improve fault detection and isolation [12–14,30,32,42,57].

However, redundancy is not free. Additional motors, sensors, converters, clutches, brakes, load paths, and control channels increase actuator mass, volume, wiring, heat generation, and verification effort. Redundancy can also introduce new interaction problems, such as force fighting, synchronization errors, and complex reconfiguration transients. Therefore, redundancy must be optimized according to the severity of the failure condition, the required availability, surface criticality, and aircraft-level architecture [12,42,58]. Two issues are particularly important in redundant EMA architectures: common-cause failures, which can reduce the effective independence of redundant channels, and force-fighting or load-sharing problems, which can create internal loads between actuators connected to the same surface. These issues are discussed next.

6.6. Common-Cause Failures, Force Fighting, and Load-Sharing Issues

Redundancy is essential for safety-critical flight-control actuation, but redundant EMA architectures do not automatically guarantee fault tolerance. If redundant channels share the same mechanical load path, power supply, cooling path, sensor reference, software function, communication link, maintenance procedure, or installation environment, they may remain vulnerable to common-cause failures. A common-cause failure is particularly critical because it can degrade or disable multiple redundant elements through a single initiating mechanism, thereby reducing the effective independence assumed in the safety assessment.

In EMA-based systems, common-cause failures may originate in several domains. Electrical examples include shared DC-bus disturbances, overvoltage during regenerative

operation, electromagnetic interference affecting multiple channels, common protection-device activation, common power-supply faults, or insulation degradation. Mechanical examples include shared bearings, structural deformation, contamination, lubrication degradation, debris propagation from a screw or gearbox, common mounting failures, or thermal expansion affecting multiple load paths. Control and software-related examples include common-mode sensor errors, erroneous load-sharing logic, incorrect reconfiguration commands, timing faults, shared communication failures, or identical software defects implemented in redundant channels. Environmental and maintenance-related examples include vibration, moisture, temperature extremes, indirect effects from lightning, connector errors, calibration mistakes, or lubrication errors affecting multiple redundant elements installed in the same region.

Therefore, fault-tolerant EMA design requires not only component redundancy but also sufficient independence between redundant elements. This independence may involve separated power feeds, independent control electronics, dissimilar sensing, physical separation, independent thermal paths, fault-containment zones, independent mechanical load paths, or, in some cases, dissimilar actuation technologies. However, increasing independence usually adds mass, volume, wiring, thermal complexity, maintenance burden, and certification effort. The design problem is therefore a trade-off between redundancy, independence, integration, and aircraft-level penalties.

A related issue in multi-actuator control surfaces is force fighting. Force fighting occurs when two or more actuators connected to the same surface command slightly different positions or generate incompatible forces. Even small differences in sensor calibration, actuator stiffness, control-loop gains, backlash, friction, latency, structural compliance, or thermal drift can cause one actuator to oppose another. This may increase structural loads, actuator currents, power losses, local heating, wear, and fatigue. In severe cases, force fighting may mask incipient faults, accelerate mechanical degradation, or reduce available control authority.

Force-fighting mitigation can be passive, active, or hybrid. Passive approaches rely on mechanical compliance, torque limiters, elastic elements, backlash management, or structural flexibility to reduce internal loads. These approaches are simple and robust, but they may reduce positioning accuracy, stiffness, or bandwidth. Active approaches use load cells, motor-current-based force estimation, position synchronization, cross-channel communication, load-equalization control, or impedance coordination to balance actuator forces. Active strategies can improve performance, but they depend on sensors, communication, control software, validation of stability margins, and robustness to sensor or communication faults. Hybrid strategies combine mechanical compliance with active load-sharing control.

Load sharing must also be considered during degraded operation. If one actuator channel is disconnected, jammed, thermally derated, current-limited, or operating with reduced dynamic capability, the remaining actuators may experience increased load, higher current peaks, and higher thermal stress. The control system must therefore coordinate load redistribution with actuator limits, structural load limits, thermal margins, and surface-level controllability. In this context, PHM information may support maintenance or reconfiguration decisions, but it should not replace the need for inherently safe load paths, reliable fault isolation, and validated degraded-mode control laws.

Table 11 summarizes representative common-cause failure and force-fighting issues in redundant EMA architectures. The table is qualitative and design-oriented; the relevance of each issue depends on the actuator architecture, control-surface criticality, redundancy concept, installation constraints, and certification assumptions.

Table 11. Common-cause failure and force-fighting issues in redundant EMA architectures.

Issue	Typical Origin	Possible Consequence	Design/Mitigation Implication
Shared electrical supply disturbance	Common DC bus, power-quality event, overvoltage during regeneration, common protection device	Simultaneous degradation or shutdown of multiple actuator channels	Independent or protected feeds, bus-voltage management, energy-absorption paths, fault-containment design
Common thermal path	Co-located power modules, shared housing, insufficient heat spreading, degraded cooling	Simultaneous thermal derating, accelerated aging, or loss of redundancy margin	Independent thermal paths, thermal zoning, derating analysis, degraded-cooling validation
Common mechanical load path	Shared screw, gearbox, bearing, structural attachment, linkage, or mounting interface	Single mechanical fault affects several redundant channels or prevents surface motion	Mechanical separation, jam-tolerant load paths, disconnect devices, structural fault containment
Common sensor or reference error	Shared position reference, calibration error, sensor drift, common signal-conditioning fault	Incorrect feedback, force fighting, erroneous fault isolation or reconfiguration	Dissimilar sensing, analytical redundancy, cross-checking, sensor-fault detection
Common software or control-law defect	Identical algorithms, timing faults, incorrect reconfiguration logic, shared communication failure	Simultaneous incorrect commands or unstable load-sharing behavior	Software assurance, robust reconfiguration logic, communication-fault handling, dissimilarity where justified
Maintenance-induced common failure	Incorrect assembly, lubrication error, connector issue, calibration mistake	Latent fault affecting multiple channels or reducing channel independence	Maintainability analysis, inspection procedures, built-in tests, configuration control
Passive force fighting	Stiff mechanical coupling, backlash, friction, tolerance mismatch, thermal expansion	Increased internal loads, wear, heating, fatigue, reduced efficiency	Mechanical compliance, tolerance control, backlash management, load-path flexibility
Active force fighting	Mismatched control gains, sensor offsets, latency, poor synchronization, load-sharing instability	Oscillatory internal loads, excessive current, thermal stress, degraded control accuracy	Load-equalization control, impedance coordination, current/force limits, stability validation
Degraded-mode load redistribution	One actuator disconnected, jammed, thermally derated, or current-limited	Overload or overheating of remaining actuators; reduced surface authority	Reconfigurable control allocation, actuator-limit monitoring, thermal-aware load sharing
PHM-dependent reconfiguration	Diagnostic uncertainty, false alarms, missed detections, delayed fault isolation	Incorrect isolation or continued operation with a degrading channel	Confidence measures, uncertainty-aware PHM, conservative safety logic, validation under representative faults

Note: The classification is qualitative and design-oriented; the relevance of each issue depends on the actuator architecture, control-surface criticality, redundancy concept, installation constraints, and certification assumptions.

Overall, the safety benefit of redundant EMA architectures depends on the independence of redundant channels, the ability to detect and isolate faults, and the management of internal loads between actuators. Common-cause failures and force fighting should therefore be addressed explicitly during architecture selection, control-law design, PHM integration, thermal assessment, and certification planning.

6.7. Fail-Safe and Fault-Tolerant EMA Architectures

Two complementary design philosophies are commonly considered in aerospace actuation: fail-safe and fault-tolerant design. In a fail-safe design, the system transitions to a safe state after a fault. In a fault-tolerant design, the system continues to operate, possibly with reduced performance, after one or more faults. For EMAs, both philosophies can be required depending on the control-surface function and failure severity [13–16,23,58].

Fail-safe behavior may be appropriate when the safest response is to remove power, engage a brake, lock a surface, disconnect a failed channel, or transfer control authority to other actuators. However, in primary flight-control systems, simply locking or disconnecting an actuator may not be sufficient if the associated surface is essential for controllability. In these cases, fault-tolerant operation is needed to maintain a minimum level of control authority.

At the mechanical level, fault-tolerant architectures aim to prevent a single blockage from immobilizing the surface. Examples include jam-tolerant mechanisms, differential ball-screw arrangements, disconnect devices, brakes, clutches, and redundant load paths [12,15,16]. Their effectiveness depends not only on the component itself, but also on the transient response during fault isolation and the remaining control authority after reconfiguration.

Experimental qualification work on fail-safe EMAs for Airbus RACER flap movable surfaces shows the importance of characterizing failure transients, brake engagement, back-driving behavior, and model-to-test correlation when demonstrating safe degraded behavior [62].

In the electrical domain, multiphase machines, dual windings, redundant converters, and fault-tolerant control laws can allow degraded operation after open-phase, switch, or winding faults [14,30–33,42]. In the control domain, reconfiguration strategies can redistribute commands among healthy channels, reduce load demand on degraded actuators, or modify control allocation at the aircraft level. The effectiveness of these solutions depends on rapid fault detection, reliable isolation, and predictable degraded-mode behavior.

A key challenge is that fault-tolerant architectures must avoid introducing new single points of failure. A disconnect mechanism can mitigate jamming, but it also becomes a component whose failure must be considered. Similarly, redundant electrical channels can improve availability, but common power supplies, shared sensors, thermal coupling, or common software may reduce the actual independence of the channels. Therefore, fault-tolerant design must be supported by a system-level safety assessment rather than by component-level redundancy alone.

6.8. Safety-Critical Design Synthesis

The safety case for EMAs must therefore be built as a multi-domain argument rather than as a component-level justification. Mechanical transmission, motor-drive architecture, sensing, control, redundancy, thermal management, and certification evidence must be co-designed to ensure that critical faults are detected, isolated, tolerated, or mitigated within the required time and performance limits [13,15,16,21,42,58]. This motivates the use of PHM, prognostics, and fault-diagnosis techniques as enabling tools for early fault detection, degradation tracking, maintenance planning, and safe reconfiguration.

7. Health Monitoring, Prognostics and Fault Diagnosis

Health monitoring and prognostics are not only maintenance-oriented functions for EMAs; they are enabling technologies for fault-tolerant electric actuation. As discussed in Section 6, EMA failure modes span mechanical, electrical, electronic, sensing, thermal, and control domains, often with tightly coupled interactions. Consequently, safe deployment

of EMAs in aircraft flight-control systems requires early detection of faults, tracking of degradation, estimation of severity, and support for maintenance and reconfiguration decisions [17,18,22,63].

In the context of MEA, PHM is particularly attractive because EMAs provide access to embedded signals that can be exploited without necessarily adding extensive external instrumentation. Motor current, voltage, position, speed, temperature, control effort, tracking error, and vibration can provide information on actuator condition, mechanical loading, friction, wear, and electrical health [17,18,64–66]. However, PHM for flight-control EMAs remains challenging because the fault signatures depend on load, temperature, command profile, aerodynamic conditions, and duty cycle, while critical fault data are scarce and often proprietary [18,65,66].

7.1. Role of PHM in EMA Reliability

The main objective of PHM in aircraft EMAs is to estimate the actuator state-of-health (SoH) before degradation evolves into loss of function or an unsafe failure condition. This role goes beyond maintenance optimization. PHM can support fault-tolerant control by detecting abnormal behavior early enough to enable safe reconfiguration, load redistribution, actuator isolation, or transition to degraded modes [17,18,63,66].

Recent work on pre-flight health monitoring for electromechanical actuation systems shows how actuator-level health management units, predefined excitation profiles, digital-twin support, and measured or synthetic data can be combined to assess EMA status before operation [67].

From an operational perspective, PHM enables condition-based maintenance by replacing fixed-interval inspection policies with decisions based on actual degradation state. This is particularly relevant for EMAs because the increase in friction, the growth of backlash, the wear of bearings, thermal aging, and power-electronics degradation may evolve progressively and leave measurable signatures in electrical or mechanical signals [18,22,64,68]. From a certification perspective, diagnostic coverage, false alarm rate, missed-detection probability, robustness to operating conditions, and response time must be assessed if PHM outputs are used to support safety-relevant decisions.

7.2. Monitored Signals and Mechanical Degradation Indicators

EMA health monitoring relies on signals that are already available in the actuator control system or can be obtained through additional instrumentation. The variables most commonly exploited include motor current, phase currents, DC-link voltage, position, speed, vibration, temperature, estimated force or torque, tracking error, and model residuals [17,18,64,69]. Their diagnostic value depends on actuator architecture, sensor placement, control strategy, and operating profile.

Mechanical degradation is one of the main targets of PHM because it is directly linked to critical failure modes such as backlash growth, increased friction, lubrication degradation, bearing failures, and incipient jamming. Backlash affects positioning accuracy, dynamic response, and load sharing, and can be estimated from position errors, motion reversals, current variations, or model-based residuals [70]. Increases in friction can indicate loss of lubrication, contamination, surface damage or bearing wear; since friction modifies the torque required to move the actuator, motor current and control effort are often useful indirect indicators [17,18,68,71].

Table 12 summarizes representative monitored signals and their diagnostic uses. The table is not intended to be exhaustive, but to illustrate how existing EMA control and protection signals can be reused for health assessment.

Table 12. Representative EMA monitored signals and diagnostic uses.

Main Diagnostic Use	Signal or Indicator
Friction increase, load variation, winding faults, open-phase faults, incipient jamming	Motor current/phase currents
Backlash, compliance, degraded tracking, sensor bias, or loss of synchronization	Position feedback/tracking error
Oscillations, mechanical looseness, friction variation and dynamic anomalies	Speed/acceleration
Bearing damage, gear wear, screw wear, misalignment, and structural looseness	Vibration
Thermal overload, insulation aging, power-electronics stress, and lubrication degradation	Temperature
Converter faults, regenerated power, overvoltage and power-quality issues	DC-link voltage/supply voltage
Load asymmetry, force fighting, model mismatch, and residual-based fault detection	Estimated force or torque/residuals
Accumulated fatigue, thermal cycling, wear progression, and maintenance planning	Duty cycle/mission profile

Note: The monitored signals and diagnostic uses are representative rather than exhaustive. Their diagnostic value depends on actuator architecture, sensor placement, operating point, control strategy, load profile, and validated PHM thresholds.

7.3. Fault Diagnosis Approaches

Fault diagnosis in EMAs aims to detect, isolate, and interpret abnormal behavior before it leads to loss of function, excessive performance degradation, or mechanical jamming. Because EMAs integrate electrical, mechanical, thermal, sensing, and control subsystems in a compact unit, no single diagnostic variable is sufficient to characterize all relevant failure modes. Instead, effective diagnosis usually requires combining embedded measurements such as motor currents, voltages, DC-link variables, position and speed signals, tracking error, temperature, vibration, estimated torque or force, and controller residuals [17,18,64–71].

Current-based diagnosis is one of the most attractive approaches because motor-current signals are already available in most EMA drives for control and protection purposes. Variations in current amplitude, harmonics, ripple, asymmetry, or transient response can provide indirect information about increased friction, load changes, bearing defects, winding faults, converter abnormalities, or incipient mechanical degradation. Current-based methods are relatively easy to implement and can be suitable for online monitoring, but their interpretation is strongly dependent on operating point, commanded motion, external load, control-loop dynamics, and power-electronics behavior. Therefore, current signatures should not be interpreted independently of the actuator mission profile and control state.

Model-based diagnosis relies on analytical or physics-based representations of the actuator to generate residuals between measured and predicted behavior. These models may include motor electrical dynamics, inverter behavior, mechanical transmission, load dynamics, friction, backlash, thermal effects, and control-loop response. Model-based methods are useful because they provide physical interpretability and can support fault isolation. For example, deviations between expected and measured position, torque, current, or temperature can indicate sensor drift, increased mechanical resistance, actuator

saturation, abnormal load torque, or degraded drive performance. However, their effectiveness depends on model accuracy, parameter identification, uncertainty management, and robustness to changing operating conditions [16,18,69].

Data-driven diagnosis uses statistical methods, machine learning, or deep learning to identify patterns associated with healthy and faulty states. These approaches are attractive when fault signatures are nonlinear, coupled, or difficult to model explicitly [68,72]. Supervised classification can be effective when labeled fault data are available, whereas unsupervised or semi-supervised methods may be more appropriate when in-service faults are rare and labeled degradation data are scarce. Data-driven methods can exploit high-dimensional combinations of current, vibration, temperature, position, speed, tracking-error, and residual features. Their main limitations are dependence on representative datasets, sensitivity to domain shift, limited interpretability, and the difficulty of demonstrating robustness under safety-critical aerospace conditions.

Hybrid approaches combine model-based residuals with data-driven classification or prognostic algorithms [66,69,73]. This combination is particularly relevant for EMAs because physics-based models can encode known relationships among electrical, mechanical, thermal, and control variables, while data-driven methods can capture nonlinear degradation signatures and residual patterns that are difficult to describe analytically. Hybrid methods may therefore improve diagnostic sensitivity and interpretability compared with purely data-driven algorithms. Nevertheless, they still require validation across representative load spectra, temperatures, duty cycles, installation conditions, and fault severities.

Recent AI-based diagnosis methods also address the problem of domain shift, which is particularly relevant for EMAs because training and operational data may differ in load spectrum, temperature, sensor location, duty cycle, and degradation severity. For example, Chen and He proposed a Transformer-based unsupervised cross-sensor domain adaptation method to improve EMA fault diagnosis when data from different sensor locations or operating conditions are used [74]. Such approaches are promising because they may reduce the dependence on fully labeled fault datasets and improve transferability across operating conditions. However, their applicability to safety-critical flight-control EMAs still requires validation under representative aerospace loads, environmental conditions, and fault progressions.

7.4. Prognostics and Remaining Useful Life Estimation

While fault detection identifies abnormal behavior, prognostics estimates the future evolution of degradation and the remaining useful life (RUL) of components. In EMAs, RUL estimation is relevant for ball screws, planetary roller screws, bearings, motor windings, power electronics and mechanical transmission elements [18,66,71]. Prognostic methods may be model-based, data-driven, or hybrid, depending on whether degradation is represented through physical laws, learned from historical data, or estimated using a combination of both approaches.

The estimation is valuable in aerospace maintenance because it can reduce unnecessary replacement of healthy components while avoiding unexpected failures. However, useful prognostics must include uncertainty bounds and must be validated under representative operating profiles. EMA degradation depends on mission profile, load spectrum, environmental conditions, duty cycle, and control strategy; therefore, prognostic indicators should be combined from several sources such as current, position, temperature, vibration, and model residuals rather than relying on a single signal [66,71].

7.5. AI-Based PHM, Digital Twins, and Validation Maturity

Building on the diagnostic and prognostic approaches discussed in Sections 7.3 and 7.4, AI-based PHM and digital twins represent a promising but still immature route for EMA health management in safety-critical flight-control applications. Their main value is not only fault classification, but also the possibility of combining embedded measurements, physics-based models, degradation indicators, and operational context to support maintenance planning, fault isolation, degraded-mode operation, and certification evidence.

AI-based methods are attractive because EMA degradation signatures are often non-linear, multi-domain, and dependent on operating conditions. Motor currents, voltages, DC-link variables, position and speed measurements, tracking error, temperature, vibration, estimated force or torque, duty-cycle information, and controller residuals can provide complementary information about electrical, mechanical, thermal, and control-related degradation. These signals may reveal incipient faults such as increased friction, backlash growth, bearing degradation, lubrication loss, sensor drift, winding faults, converter degradation, abnormal load behavior, or incipient jamming [17,18,64–71].

However, the maturity of AI-based PHM methods depends strongly on the representativeness of the validation data. Many published approaches are validated using simulations, synthetic degradation scenarios, seeded faults, or laboratory EMA test rigs. These studies are valuable because they allow controlled fault injection, repeatability, and algorithm benchmarking. Nevertheless, they do not necessarily reproduce the full combination of aerodynamic loads, thermal gradients, vibration, installation effects, electrical-network interactions, maintenance variability, and environmental conditions encountered in aircraft operation. Therefore, the distinction between algorithm demonstration and flight-representative validation is essential when assessing PHM readiness.

Digital twins can help bridge this gap by combining physics-based EMA models with operational data and diagnostic algorithms. A useful digital twin for flight-control EMAs should represent the coupled electrical, mechanical, thermal, and control behavior of the actuator, including motor-drive dynamics, converter losses, screw or gearbox friction, thermal paths, backlash, degradation progression, and load-dependent behavior. The required model fidelity depends on the intended use. A twin used for maintenance advisory functions may tolerate larger uncertainty than a twin used to support safety-critical decision-making, degraded-mode operation, or certification credit.

For certifiable EMA PHM, uncertainty management is as important as diagnostic accuracy. False alarms can reduce dispatch reliability and increase unnecessary maintenance, whereas missed detections can allow degradation to progress toward loss of function or jamming. Therefore, PHM outputs should include confidence measures, uncertainty bounds, robustness to sensor faults, and explicit limits of validity. In addition, the PHM system itself must be assessed as part of the safety architecture if it is used for maintenance interval extension, fault isolation, degraded-mode operation, or certification credit.

A major unresolved challenge is the scarcity of open degradation datasets obtained under flight-representative conditions. Publicly available laboratory platforms and fault-injection benches are valuable for method development, but their results should not be interpreted as equivalent to in-service aircraft validation unless the load spectrum, thermal environment, vibration, duty cycle, and failure progression are representative of the target application. This gap between laboratory PHM and flight-representative PHM remains one of the main barriers to using AI or digital twins as more than advisory monitoring tools.

To clarify this issue, Table 13 summarizes different validation maturity levels for PHM and digital-twin approaches in EMAs. The classification is qualitative and design-oriented; its purpose is to distinguish early algorithm demonstration from evidence that could support aerospace integration, qualification, or certification-oriented use.

Table 13. Validation maturity levels for PHM and digital-twin approaches in EMAs.

Validation Level	Typical Evidence Source	Main Strengths	Main Limitations	Relevance for Aircraft EMA Certification
Simulation-based validation	Analytical models, numerical degradation models, synthetic faults, simulated sensor signals	Low cost, controllable conditions, useful for early algorithm screening	May not reproduce real degradation physics, sensor noise, environmental variability, or coupled faults	Useful for concept development, but insufficient as certification evidence
Benchtop EMA test rig	Laboratory actuator rig, controlled loads, seeded faults, repeated experiments	Enables repeatable fault injection and comparison of diagnostic algorithms	Load spectra, thermal conditions, vibration, installation effects, and environmental stresses may be simplified	Valuable for PHM development, but requires further validation before safety credit
Component-level accelerated testing	Bearings, screws, gears, motors, power modules, sensors tested under accelerated stress	Provides degradation data and failure progression for specific components	Component behavior may not capture system-level coupling or actuator-control interactions	Supports reliability models, maintenance thresholds, and degradation indicators
Hardware-in-the-loop/iron-bird validation	Real actuator hardware integrated with control electronics, simulated flight loads, representative commands	Captures actuator–control interaction and more realistic duty cycles	Still may not fully reproduce aircraft installation, thermal boundary conditions, vibration, or long-term operation	Stronger evidence for integration and degraded-mode assessment
Flight-representative ground testing	Actuator tested under realistic load spectra, thermal conditions, vibration, and environmental constraints	Provides realistic operating and degradation conditions without flight risk	Expensive, application-specific, and difficult to generalize	Important for qualification, PHM threshold validation, and safety-case support
Aircraft operational data	In-service actuator data, maintenance records, real mission profiles, environmental exposure	Highest operational relevance and true mission variability	Often proprietary, scarce, difficult to label, and affected by incomplete fault observations	Most valuable for mature PHM, reliability estimation, and certification confidence
Certification-oriented PHM validation	Verified PHM algorithms, uncertainty bounds, false-alarm/missed-detection analysis, configuration control, and safety assessment	Directly addresses reliability and acceptability of PHM outputs	Requires rigorous evidence, traceability, validation datasets, and accepted means of compliance	Required if PHM is intended to support safety credit, maintenance extension, or degraded operation

Note: The classification is qualitative and design-oriented. It distinguishes early algorithm demonstration from evidence that could support aerospace integration, qualification, or certification-oriented use.

Overall, AI-based diagnosis and digital twins should be considered enabling tools for EMA maintainability and reliability, but not automatic substitutes for fault-tolerant mechanical and electrical design. For secondary flight-control surfaces, PHM may first provide maintenance advisory functions and dispatch support. For primary flight-control applications, stronger evidence is required: representative degradation datasets, validated multi-domain models, uncertainty-aware algorithms, robustness to sensor faults, and a clear certification argument defining whether PHM is advisory or safety-creditable. Therefore, future work should focus not only on improving diagnostic accuracy, but also on demonstrating PHM reliability under representative aerospace loads and on defining acceptable evidence for certification-oriented use.

8. Specific Knowledge Gaps and Future Research Directions

Despite substantial progress, EMAs still face coupled technical, operational, and certification barriers before they can be widely deployed in safety-critical flight-control applications. However, these barriers should not be interpreted only as generic open challenges. For certifiable flight-control EMAs, the key unresolved issues are specific and evidence-driven: the absence of widely accepted means of compliance for some failure conditions, limited public failure-rate data under representative aerospace loads, insufficient operational experience compared with mature hydraulic systems, incomplete validation of jam-tolerant mechanisms, limited flight-representative PHM datasets, and the need to demonstrate robust behavior under combined electrical, thermal, mechanical, and control faults.

Therefore, the remaining research needs are not independent topics but interrelated design and certification questions. Mechanical jamming, thermal concentration, wide-bandgap (WBG) power-electronics reliability, high-voltage electrical integration, PHM maturity, and common-cause failures interact at the aircraft level. The central challenge is to demonstrate that EMAs can provide not only power-on-demand operation and maintainability benefits, but also predictable degraded behavior, robust thermal performance, electrical-network compatibility, reliable health monitoring, and certifiable safety margins under representative flight-control loads.

Table 14 summarizes the main knowledge gaps identified in this review and translates them into actionable research directions for the development of certifiable EMA-based flight-control systems.

Table 14. Specific knowledge gaps and actionable research directions for certifiable EMA flight-control systems.

Knowledge Gap	Why It Remains Unresolved	Evidence Currently Missing	Design/Certification Impact	Actionable Research Direction
Certification means of compliance for primary-surface EMAs	EMAs introduce coupled mechanical, electrical, thermal, control, and software failure modes that differ from mature hydraulic architectures.	Accepted compliance strategies for jammed-load paths, degraded operation, electronic hardware/software assurance, and PHM-supported maintenance credits.	Limits the use of EMAs in primary flight-control surfaces, where failure consequences are severe.	Develop certification-oriented EMA design processes aligned with aircraft-level safety assessment, environmental qualification, software/hardware assurance, and representative fault-injection evidence.
Public failure-rate and reliability data	Many EMA reliability data are proprietary, application-specific, or derived from laboratory tests rather than long-term flight operation.	Public failure-rate data for screws, bearings, gearboxes, motors, converters, sensors, and control electronics under flight-representative duty cycles.	Reduces confidence in quantitative safety assessment and comparison with mature hydraulic systems.	Establish shared reliability databases, accelerated-life test protocols, and mission-profile-based degradation models for aerospace EMAs.
Mechanical jamming and jam-tolerant load paths	Screw-based transmissions can create direct mechanical blockage of the control surface, and the effectiveness of mitigation concepts depends strongly on architecture.	Comparative validation of differential screws, disconnect devices, clutches, torque limiters, redundant load paths, anti-jamming transmissions, and surface-level redundancy.	Jamming remains one of the main barriers to primary flight-control EMA certification.	Compare anti-jamming concepts using common criteria: residual controllability, added mass, failure detectability, response time, maintainability, and certification evidence.

Table 14. Cont.

Knowledge Gap	Why It Remains Unresolved	Evidence Currently Missing	Design/Certification Impact	Actionable Research Direction
Life prediction of screw-based transmissions	Ball screws and planetary roller screws are affected by load spectra, lubrication, preload, backlash, wear, contact fatigue, thermal expansion, and contamination.	Public L10/life data under representative aerospace load cycles, temperature ranges, vibration, and lubrication conditions.	Makes it difficult to link mechanical degradation to inspection intervals, PHM thresholds, and safety margins.	Develop mission-profile-based life models and validate them through accelerated testing, tribological monitoring, and degradation-aware mechanical design.
Mission-level energy-efficiency assessment	EMA benefits depend on duty cycle, control-surface activity, hydraulic standby losses avoided, electrical-network losses, cooling penalties, and redundancy overhead.	Comparable mission-level energy data for SHA, EHA, EBHA, and EMA architectures using common aircraft classes, flight phases, and surface-load profiles.	Qualitative efficiency claims may overestimate or underestimate aircraft-level benefits.	Develop benchmark mission profiles and open simulation frameworks that combine actuator losses, aircraft-level mass effects, thermal-management penalties, and regenerated-power handling.
Thermal management and local heat rejection	EMAs concentrate losses in motors, converters, bearings, screws, and housings, while installation locations may offer limited cooling capacity.	Validated thermal impedance models, thermal cycling data, cooling-system mass penalties, and temperature limits under peak and repeated transient loads.	Thermal constraints can reduce continuous performance, accelerate aging, and offset energy-efficiency benefits.	Compare structural conduction, forced-air cooling, liquid cooling, thermal interface materials, phase-change materials, derating, and integrated electro-thermal design.
WBG power-electronics robustness and EMI/EMC	SiC and GaN devices improve efficiency and power density but increase dv/dt , EMI, insulation stress, and thermal-cycling concerns.	Long-term aerospace reliability data for WBG converters, converter topology comparisons, EMI/EMC evidence, insulation coordination, and thermal cycling under EMA duty cycles.	Converter failures and electromagnetic interference can affect actuator availability and nearby safety-critical systems.	Develop EMI-aware layouts, converter-health monitoring, topology-level comparisons, insulation strategies, and integrated WBG drive qualification procedures.
Common-cause failures in redundant EMA architectures	Redundant channels may still share power supplies, cooling paths, sensors, software, structural attachments, or environmental exposures.	Explicit common-cause failure analysis for redundant actuators, multi-actuator surfaces, shared DC buses, cooling systems, and control software.	Redundancy may not provide the expected safety benefit if common dependencies are not eliminated or mitigated.	Integrate common-cause analysis with architecture selection, physical separation, dissimilar redundancy, independent sensing, thermal decoupling, and robust power-distribution design.
Force fighting and load sharing	Multiple actuators driving the same surface can generate internal loads due to position mismatch, stiffness differences, sensor errors, or control delays.	Comparative evidence for passive compliance, force equalization, impedance coordination, load-sharing loops, and reconfiguration after actuator faults.	Poor load sharing can increase structural loads, reduce efficiency, accelerate wear, and complicate certification.	Develop validated multi-actuator control strategies that combine position tracking, force equalization, impedance coordination, and fault-tolerant reconfiguration.
PHM and digital-twin maturity	Many PHM methods are validated on simulations or benchtop rigs, while flight-representative fault data are scarce.	Degradation datasets under realistic loads, uncertainty bounds, validation against physical faults, robustness to sensor faults, and evidence for certification acceptance.	PHM may remain advisory rather than certifiable unless its reliability and limitations are demonstrated.	Develop hybrid physics/data-driven PHM, explainable AI, uncertainty-aware digital twins, standardized fault datasets, and validation campaigns under representative flight-control loads.

Table 14. Cont.

Knowledge Gap	Why It Remains Unresolved	Evidence Currently Missing	Design/Certification Impact	Actionable Research Direction
Primary versus secondary flight-control applicability	Failure consequences differ greatly between primary and secondary surfaces, but EMA maturity is often discussed generically.	Surface-specific evidence for acceptable degraded modes, jam tolerance, redundancy allocation, and operational consequences.	Overgeneralized conclusions may obscure where EMAs are already suitable and where barriers remain critical.	Separate EMA adoption pathways for secondary surfaces, high-lift systems, spoilers, trim systems, and primary flight-control surfaces.
Standardization and validation infrastructure	EMA designs are highly application-specific, which makes comparison, qualification, and certification evidence difficult to generalize.	Common test protocols, benchmark load profiles, hardware-in-the-loop setups, iron-bird validation data, and standardized reporting of mass, efficiency, thermal, and reliability metrics.	Slows technology transfer and makes evidence accumulation fragmented.	Promote modular EMA architectures, standardized interfaces, open benchmark cases, and flight-representative validation procedures.

Note: The gaps and research directions listed are representative of the evidence needs identified in this review. Their priority depends on the aircraft class, control-surface criticality, actuator architecture, redundancy concept, certification basis, and operational environment.

8.1. Certification and Application Pathways for Primary and Secondary Flight Controls

Certification remains one of the main barriers to using EMAs in safety-critical flight-control applications, but the required evidence depends strongly on the criticality of the control surface. For primary flight-control surfaces, such as ailerons, elevators, rudders, or equivalent fly-by-wire control surfaces, the safety case must cover nominal performance, fault detection, fault isolation, degraded operation, common-cause failures, software and electronic hardware assurance, environmental qualification, and aircraft-level effects [57,58,75–79]. In these applications, loss of motion, uncontrolled motion, or mechanical jamming may have hazardous or catastrophic consequences depending on the aircraft architecture and flight condition.

For secondary flight-control surfaces, such as flaps, slats, spoilers, trim systems, or selected high-lift devices, the certification path may be less demanding, although still safety-relevant. In these cases, the main design drivers may include dispatch reliability, maintainability, energy efficiency, reduction in hydraulic infrastructure, and safe isolation after failure. A fail-safe response, controlled disconnection, or surface locking may be acceptable if aircraft-level controllability, handling qualities, and operational safety remain satisfied.

This distinction is important because conclusions drawn from secondary-surface applications, experimental demonstrators, or non-critical actuation functions cannot be transferred directly to primary flight-control systems. Secondary applications may tolerate architectures in which a failed actuator is isolated or locked, whereas primary applications may require continued operation with reduced authority, jam-tolerant mechanical design, independent redundant channels, validated degraded-mode control, or compensation through other control surfaces.

Therefore, future research should avoid treating EMA readiness as a single generic maturity level. EMA adoption should be evaluated as a function of surface criticality, failure severity, redundancy architecture, available aircraft-level control allocation, thermal environment, maintainability requirements, and certification evidence. This perspective helps identify where EMAs can be deployed with lower certification risk and where further validation, standardization, and safety-case development are still required.

8.2. Jamming Mitigation and Fault-Tolerant Mechanical Design

Mechanical jamming remains the most distinctive challenge in EMA safety. Screw mechanisms, bearings, gears and load-path components can degrade through wear, loss

of lubrication, contamination, fatigue, overload, or thermal effects, potentially leading to friction growth or complete blockage [15,16,26–28,60].

Promising directions include redundant load paths, differential screw concepts, disconnect or clutch devices, jam-tolerant transmissions, improved tribology, and design rules. These solutions must be evaluated not only for nominal performance but also for added mass, new failure modes, inspection requirements, and certifiable fault coverage.

8.3. High-Voltage Electrical Networks, Power Electronics, and Protection

EMA deployment is closely related to high-voltage aircraft electrical networks. Higher voltage can reduce current and cable mass, but increases challenges related to insulation coordination, partial discharge, arcing, wiring degradation, protection selectivity, and EMC [80–85]. These issues become especially relevant when several power-electronic loads, actuator drives, converters, energy-storage interfaces, and regenerative subsystems operate on the same aircraft electrical network.

Power electronics are a parallel enabler and constraint. SiC and GaN devices can improve efficiency and power density, but also increase demands on EMI/EMC control, insulation design, thermal cycling, packaging reliability and lifetime prediction [9,21,40,41,82]. Therefore, future work should co-design converters, machines, wiring, filtering, grounding, protection, and health monitoring.

Future EMA integration should also consider system-level stability in power-electronics-dominated MEA architectures. EMA drives may generate current peaks during fast surface motion, return energy to the DC link during regenerative operation, and interact with other converters through common buses, filters, protection devices, and control loops. Although not specific to aircraft EMAs, recent work on solid-state transformers has shown that AC-DC port coupling and converter control-loop interactions can produce low-frequency oscillations, and that multiport dissipativity analysis can help identify whether instability originates from local port behavior or coupling dynamics [86]. Similar stability concepts may become relevant as EMA drives increasingly operate as networked power-electronic loads.

Therefore, future research should extend EMA power-electronics analysis beyond component efficiency and converter topology to include bus-stability assessment, regenerative-energy handling, impedance/admittance-based interaction analysis, protection coordination, EMI/EMC-aware layouts, WBG-device lifetime prediction, and validation under representative actuator duty cycles and degraded electrical-network conditions.

8.4. Thermal Management and Multiphysics Co-Design

Thermal management remains a limiting factor for compact high-performance EMAs. Losses are concentrated in motors, converters, bearings, gears, screw mechanisms, and structural interfaces, while available cooling paths in wings or tail sections can be limited [48,49,52].

Future EMA development should use multiphysics co-design rather than sequential sizing. Electromagnetic design, converter losses, mechanical efficiency, structural heat paths, redundancy, degraded-mode operation, and mission load profiles must be evaluated together to avoid architectures that are efficient in nominal analysis but thermally fragile in service.

8.5. PHM, AI, and Digital Twins for Certifiable EMA Operation

PHM, AI-based diagnosis, and digital twins can support reliability, maintenance planning, and management of the degradation mode, but their use in safety-critical flight controls is limited by limited fault data, proprietary datasets, limited flight-

representative validation, uncertainty quantification, and certification of learning-based algorithms [63–66,68–73,87].

The most promising route is hybrid PHM that combines physics-based models, embedded measurements, and data-driven learning. Digital twins may support virtual testing, degradation simulation, maintenance planning, and certification evidence, but they must be validated against representative loads, temperatures, vibration, faults, and environmental conditions.

8.6. Standardization, Validation, and Aircraft-Level Co-Optimization

Standardization and validation are essential to move EMAs from prototypes to deployable aircraft systems. Application-specific designs increase development cost and complicate qualification, whereas modular actuator architectures, standardized interfaces, and reusable test protocols can improve scalability across aircraft platforms. European programs such as ACTUATION2015 and FLIGHT-EMA illustrate the importance of coordinated development for aerospace EMAs [88,89].

Representative validation should include full-scale actuator testing, hardware-in-the-loop experiments, iron-bird or copper-bird integration, environmental qualification, fault-injection campaigns, endurance testing, and mission-level energy assessment. This evidence is needed to connect subsystem-level performance with aircraft-level safety, efficiency, and maintainability.

Ultimately, the path toward fully electric primary actuation requires aircraft-level co-optimization. The optimal architecture is not the one that maximizes actuator efficiency alone, but the one that minimizes mission-level penalties while satisfying safety, reliability, thermal, electrical-network, maintenance, and certification constraints.

8.7. Design Framework for Certifiable EMA-Based Flight-Control Systems

The preceding challenges indicate that certifiable EMA-based flight-control systems cannot be assessed through isolated component metrics alone. The main design question is not only whether an EMA can deliver the required force, stroke, bandwidth, and efficiency, but whether it can do so under representative mission loads, thermal constraints, degraded conditions, redundancy assumptions, and certification requirements.

Table 15 summarizes a proposed design checklist for EMA-based flight-control systems. The checklist is intended as a synthesis tool for early architecture selection and technology-readiness assessment. It does not replace aircraft-level safety assessment, certification procedures, or detailed qualification plans, but it identifies the main evidence categories that should be addressed before EMAs can be considered suitable for safety-critical flight-control applications.

Table 15. Design checklist for certifiable EMA-based flight-control systems.

Design Dimension	Key Question	Evidence Required	Main Certification/Design Implication
Surface criticality	Is the EMA intended for a primary or secondary flight-control surface?	Failure-condition classification, aircraft-level controllability analysis, degraded-mode requirements	Determines whether fail-safe isolation is sufficient or continued fault-tolerant operation is required
Mechanical transmission	Can the screw, gearbox, bearing, brake, or no-back-device elements tolerate or mitigate degradation and jamming?	Load spectra, L10/life assessment, wear and lubrication analysis, jam-tolerance tests, failure-progression evidence	Mechanical jamming remains one of the main barriers for primary flight-control EMAs

Table 15. Cont.

Design Dimension	Key Question	Evidence Required	Main Certification/Design Implication
Motor and winding architecture	Does the motor provide sufficient torque, efficiency, thermal margin, and fault tolerance?	Torque-speed envelope, efficiency map, winding configuration, thermal model, degraded-mode capability	Motor selection must consider not only nominal performance but also failure behavior and cooling limits
Power electronics	Can the converter tolerate current peaks, regeneration, EMI/EMC constraints, and degraded operation?	Converter-topology assessment, protection logic, thermal impedance, DC-link behavior, EMI/EMC tests	Power electronics must be treated as part of the safety-critical actuator architecture
Thermal management	Can heat be rejected under nominal, transient, and degraded conditions?	Electro-thermal model, cooling strategy, thermal-path validation, derating analysis, degraded-cooling cases	Component-level efficiency is insufficient without aircraft-level thermal integration
Redundancy independence	Are redundant channels sufficiently independent?	Common-cause failure analysis, separated power/sensing/control/thermal paths, fault-containment assessment	Redundancy provides safety benefit only if independence assumptions are justified
Force fighting and load sharing	Can multiple actuators share load without harmful internal forces?	Load-equalization logic, impedance coordination, synchronization analysis, stability validation	Multi-actuator surfaces require explicit internal-load management
Fault detection and PHM	Can degradation be detected, isolated, and interpreted before unsafe behavior occurs?	Sensor set, diagnostic coverage, uncertainty bounds, false-alarm and missed-detection analysis	PHM may support maintenance or reconfiguration, but safety credit requires strong validation
Digital twin/model fidelity	Is the model suitable for the intended decision function?	Multi-domain model validation, parameter uncertainty, operational-data correlation	Advisory twins and safety-credible twins require different levels of evidence
Aircraft electrical integration	Does the EMA interact safely with the aircraft electrical network?	Power-quality analysis, regenerative-energy handling, bus-stability assessment, protection coordination	EMA drives must be assessed as networked electrical loads, not isolated actuators
Maintainability	Can inspection, replacement, lubrication, calibration, and fault isolation be performed reliably?	Maintenance procedures, built-in tests, access constraints, configuration control	Maintenance-induced common failures must be considered
Validation maturity	Has the architecture been validated beyond simulation or benchtop testing?	Hardware-in-the-loop or iron-bird tests, flight-representative ground testing, environmental qualification, operational data where available	Certification confidence depends on representative validation, not only algorithm or component demonstration

Note: This checklist is qualitative and design-oriented. The relevance and required depth of each item depend on aircraft class, control-surface criticality, actuator architecture, load spectrum, redundancy concept, thermal environment, maintainability requirements, and certification assumptions.

9. Conclusions

This review has analyzed electromechanical flight-control actuation systems within the more-electric aircraft paradigm, focusing on the relationships between architecture, energy efficiency, fault tolerance, health monitoring, thermal integration, and certification-oriented design. EMAs offer clear potential benefits, including power-on-demand operation, elimi-

nation of hydraulic leakage, distributed control, improved observability, and compatibility with advanced electrical architectures. However, their adoption in safety-critical flight controls is limited by mechanical jamming, thermal concentration, power-electronics reliability, redundancy overhead, PHM validation, and certification evidence.

Comparison among SHAs, EHAs, EBHAs, and EMAs shows that no technology is universally superior. SHAs remain mature and force-dense but carry aircraft-level hydraulic penalties. EHAs and EBHAs support incremental electrification, with EHAs improving efficiency through local power generation and EBHAs strengthening redundancy through electrical backup. EMAs provide the strongest route to fully electric actuation, but only if their mechanical, electrical, thermal, control, monitoring, and safety challenges are addressed at the system level.

The main conclusion is that EMAs should not be treated as direct component-level replacements for hydraulic actuators. Their successful deployment requires integrated co-design of transmissions, motors, converters, sensors, control laws, thermal paths, redundancy, PHM, and certification evidence. In this context, the transition towards fully electric actuation should be understood not as a technological substitution, but as a paradigm shift in the way flight-control systems are designed, integrated, and certified.

Future research should prioritize jam-tolerant mechanisms, high-reliability motor drives, high-voltage integration, multiphysics thermal design, validated PHM and digital twins, modular architectures, and representative experimental validation under aircraft-relevant load profiles.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
DAL	Design Assurance Level
DC	Direct Current
EBHA	Electro-Backup Hydraulic Actuator
EHA	Electro-Hydrostatic Actuator
EMA	Electromechanical Actuator
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FMECA	Failure Modes, Effects, and Criticality Analysis
HIL	Hardware-in-the-Loop
HVDC	High-Voltage Direct Current
LVDT	Linear Variable Differential Transformer
MEA	More-Electric Aircraft
PHM	Prognostics and Health Management
RUL	Remaining Useful Life
RVDT	Rotary Variable Differential Transformer
SHA	Servo-Hydraulic Actuator

SoH	State of Health
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
WBG	Wide-Bandgap

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