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RESEARCH ARTICLE

MORPHING WING TECHNOLOGIES FOR UNMANNED AERIAL VEHICLES: A CRITICAL REVIEW OF AERODYNAMICS, ACTUATION, AEROELASTICITY, FLIGHT DYNAMICS, AND ADAPTIVE CONTROL TECHNOLOGIES

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Abstract

Morphing wings allow an aircraft to change aerodynamic configuration during flight, offering a means to reconcile competing requirements across take-off, climb, cruise, loiter, manoeuvring and landing. This critical review synthesizes 56 traceable sources on fixed-wing UAV/small-aircraft morphing through 2026. The literature is organized by geometric degree of freedom planform/span, camber and airfoil shape, twist/dihedral/wingtip, and distributed or bio-inspired morphing and cross classified by actuation, aerodynamic and mission metrics, aeroelastic consequence and validation level. Rather than pooling heterogeneous results, the review preserves study specific baselines and distinguishes analytical, numerical, wind tunnel, ground/bench and flight evidence. A central finding is that aerodynamic improvement is not synonymous with aircraft-level benefit: selected studies commonly report 10 to 30% improvements in aerodynamic metrics, while mission-level gains can be reduced by actuator and structural mass. The review also corrects an important literature-record error: the approximately 5.5% endurance benefit belongs to the Zigzag wingbox study, whereas the 2018 Transformer UAV reported larger study specific endurance and range gains under its stated conditions. Morphing also changes stiffness, inertia and aerodynamic derivatives, making flutter, divergence and control authority integral design constraints. AI-assisted optimization is increasingly useful offline, but real-time, flight-validated and fault-tolerant adaptive morphing remains immature. The review therefore proposes a deployment-oriented framework that optimizes morphing against mission objectives subject to mass, power, structural, aeroelastic and control constraints.

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Nomenclature:-Key abbreviations used in this review: L/D, lift-to-drag ratio; Re, Reynolds number; C_D, drag coefficient; C_L, lift coefficient; TRL, Technology Readiness Level.

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Introduction:-

A fixed wing is inherently a compromise. A configuration that is efficient in cruise is rarely simultaneously optimal for short take-off, high lift manoeuvring, low speed landing, sustained loiter and high speed transit. Conventional aircraft resolve these conflicts with discrete devices such as flaps, slats, ailerons and trim surfaces. Morphing wings seek a more continuous solution by changing span, sweep, reference area, camber, thickness distribution, twist, dihedral, wingtip geometry or local incidence during flight. The foundational UAV review by Ozel, Ozbek and Ekici established this motivation and documented early applications ranging from flexible micro air vehicle wings to span, camber and winglet morphing [26].

UAVs frequently operate over wide mission envelopes and impose severe mass, volume and power constraints. A small vehicle may need to climb rapidly, loiter efficiently, manoeuvre around obstacles, tolerate gusts and then land in a confined area. These competing requirements make variable geometry attractive. At the same time, the small scale of many UAVs makes actuator mass, battery consumption, skin friction, Reynolds-number effects and manufacturing tolerances disproportionately important. Consequently, a morphing concept should be judged by its net aircraft level benefit rather than by aerodynamic coefficients alone.

The present work extends the UAVspecific foundation established by Ozel et al. [26] rather than reproducing it. Subsequent reviews have broadened the field to morphing-aircraft design and control [40, 44], AI-integrated morphing architectures [31], bio inspired morphing across aerospace and renewable-energy applications [27], and experimentally verified morphing-wing studies [55]. A 2026 review further synthesizes aerodynamic and aeroelastic progress across chordwise, spanwise and planform morphing and emphasizes the remaining gap between models and practical implementation [56]. The present review is deliberately narrower in application and more deployment oriented than these broader reviews: it focuses specifically on fixed wing UAV/small aircraft morphing, and links geometry, actuation, aerodynamic performance, mission-level benefit, aeroelasticity and adaptive control within one evidence framework.

In particular, unlike [26], the review updates the UAV specific literature; unlike [27], it excludes the broader aerospace/renewable energy bioinspiration scope; unlike [31], it treats AI as one component of a wider deployment chain rather than the principal organizing theme; unlike [55], it emphasizes evidence level and aircraft-level net benefit rather than experimental verification alone; and unlike [56], it is application-focused on UAV/small-aircraft deployment and explicitly connects morphing performance to actuator/structural burden, mission metrics and control constraints.

Research questions:-

RQ1: Which geometric degrees of freedom and structural architectures are used for UAV morphing wings, and what missions do they address?

RQ2: What aerodynamic and mission level improvements have actually been demonstrated, and at what validation level?

RQ3: How do actuator mass, response speed, stroke, energy consumption and controllability constrain morphing wing design?

RQ4: How does morphing alter flutter, divergence, stability and control, and how should these effects be integrated into the design process?

RQ5: What roles do optimization, surrogate modelling, machine learning and adaptive control play, and how close are these methods to flight deployment?

RQ6: What evidence gaps currently prevent reliable translation from laboratory morphing mechanisms to operational UAVs?

Review Method and Evidence Framework:-

Review type and scope:-

This manuscript is framed as a critical/narrative review with a structured evidence classification framework, not as a formal PRISMA systematic review or meta analysis. The scope covers fixed wing UAV and small aircraft morphing wings, including planform, section shape, twist/wingtip and distributed or bio inspired morphing. Sources were retained when they contained traceable technical evidence concerning a morphing mechanism, actuator, aerodynamic metric, mission metric, aeroelastic consequence or flight control implication. Conference papers and preprints are retained only when they add distinctive technical evidence; peer reviewed journal sources are given greater interpretive weight.

Evidence hierarchy:-

To avoid treating CFD percentages and flight demonstrations as equivalent, quantitative claims are coded using five validation levels: Level I: analytical/theoretical; Level II: CFD/FEA/numerical; Level III: wind-tunnel experiment; Level IV: ground or bench hardware; and Level V: flight demonstration. The level refers to the evidence supporting the specific numerical claim, not necessarily the highest level reached by the entire study. The framework is ordinal rather than a formal quality score. Flight evidence is assigned the highest operational relevance level, not assumed to be intrinsically more rigorous than a well controlled wind tunnel experiment; repeatability, uncertainty and test conditions still determine evidentiary strength.

Level	Evidence	Typical strength	Primary limitation
I	Analytical/theoretical	Mechanistic insight; fast parameter studies	Idealized assumptions
II	CFD/FEA/numerical	Detailed geometry and parametric exploration	Model-form and validation dependence
III	Wind tunnel	Direct aerodynamic measurement	Scale/Reynolds-number and facility effects
IV	Ground/bench hardware	Real actuator/structure behaviour	Does not prove free-flight benefit
V	Flight demonstration	Highest operational relevance	Often limited sample size and conditions

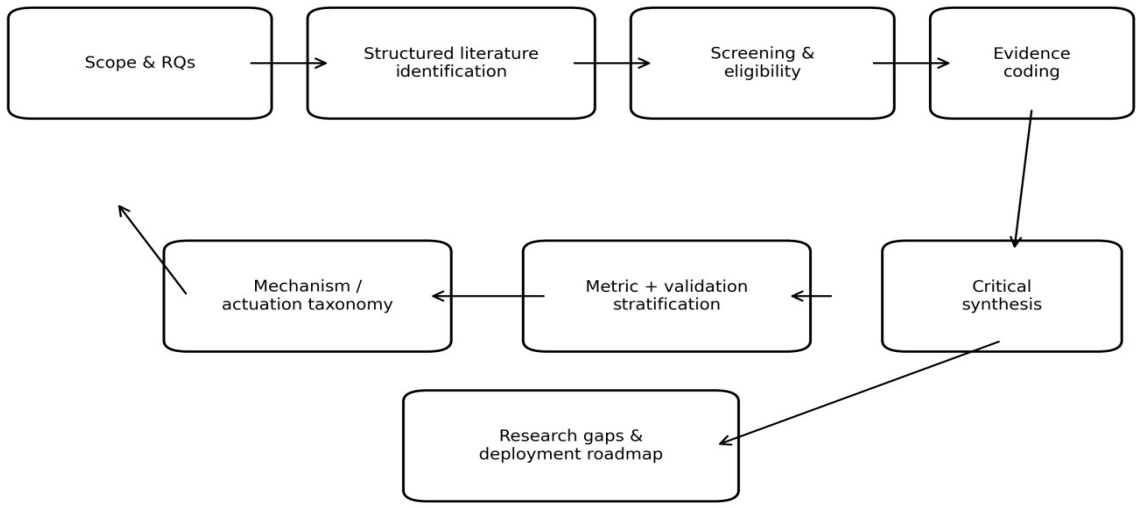

Figure 1 illustrates the structured workflow employed: literature identification and triage, evidence-level coding, taxonomy classification, metric extraction, and cross cutting synthesis.

Evidence extraction and metric discipline:-

For each source, the review records the morphing degree of freedom, actuation method, baseline, reported metric, validation level, and mission relevance. Reported values are not pooled into a single effect size because the underlying studies use different Reynolds numbers, wing geometries, morphing amplitudes, operating conditions and performance definitions. Percentages are therefore presented as study-specific observations, with their validation level and baseline retained.

Search strategy and screening protocol:-

To improve reproducibility without overstating the historical search record, the review now documents the search concepts and Boolean logic used to identify the literature. The intended search frame was 2000 to 2026 and focused on fixed wing UAV/small aircraft morphing. Three concept blocks were used: (A) morphing/adaptive geometry, (B) UAV/small aircraft context, and (C) performance/control/aeroelastic terms. Representative database ready strings are given below and can be reproduced with field-specific syntax in Scopus, Web of Science, IEEE Xplore, and

Google Scholar. Because the original search log did not preserve database by database hit counts, this revision does not fabricate retrospective PRISMA numbers.

Source / platform	Documented Boolean search string
Scopus / Web of Science	("morphing wing" OR "adaptive wing" OR "morphing aircraft" OR "adaptive aircraft" OR "variable geometry wing") AND ("UAV" OR "unmanned aerial vehicle" OR "drone" OR "small aircraft")
Scopus / Web of Science: mechanism expansion	(("morphing wing" OR "adaptive wing") AND ("span morphing" OR "planform morphing" OR "camber morphing" OR "twist morphing" OR "wingtip morphing" OR "distributed morphing")) AND ("UAV" OR "unmanned aerial vehicle" OR "small aircraft")
Scopus / Web of Science: systems expansion	(("morphing wing" OR "adaptive wing") AND ("actuator" OR "aeroelastic*" OR "flutter" OR "divergence" OR "flight control" OR "adaptive control" OR "machine learning" OR "optimization")) AND ("UAV" OR "unmanned aerial vehicle" OR "drone")
Google Scholar	"morphing wing" UAV OR "unmanned aerial vehicle" adaptive wing; supplemented by the mechanism and systems strings above
Backward / forward tracing	Reference-list screening and cited-by tracing from high-relevance foundational and recent review/study papers.

Screening, eligibility and record integrity:-

Eligibility was defined at the study level. Included sources had to (i) address a morphing/adaptive wing or closely related morphing flight control architecture, (ii) contain traceable technical evidence relevant to at least one review question, and (iii) fall within the 2000 to 2026 search window unless an earlier source was necessary as a foundational work. Peer reviewed journal articles were prioritized. Conference papers, theses/institutional reports and preprints were retained only when they supplied distinctive evidence such as a demonstrator, flight test, mechanism, or historical foundation. Sources were excluded when they were outside the fixed wing UAV/small aircraft scope without a transferable technical contribution, lacked traceable bibliographic information, or duplicated evidence already represented by a more complete source. Title/abstract relevance was followed by full-text technical screening and extraction of morphing degree of freedom, actuation, baseline, metric, validation level and mission relevance. Reference integrity was checked against the bibliography before quantitative claims were retained. The final manuscript contains 56 numbered references, consistent with the source count stated in the Abstract.

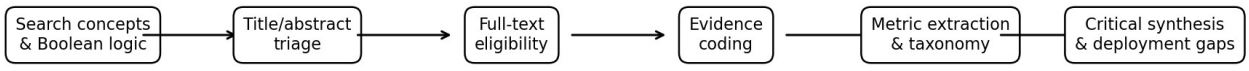

Figure 1. Reproducible critical-review workflow (No unobserved database hit or screening counts are inferred retrospectively)

Source-quality classification:-

The bibliography is intentionally differentiated by source type. Peer-reviewed journal articles constitute the principal evidence base; conference proceedings and institutional reports are used mainly for early demonstrators and flight-test programmes; arxiv is retained only for a narrowly scoped commercial-aviation review [28]. The revised manuscript does not use non peer reviewed web pages as primary quantitative evidence, because such sources typically lack the methodological transparency required by the evidence hierarchy used in this review.

Morphing-Wing Taxonomy:-

A useful UAV design taxonomy should begin with the geometric variable that must change, because the required aerodynamic function determines the structural architecture and actuator. The revised taxonomy therefore separates planform, section-shape, out of plane and distributed/bio inspired morphing, while treating materials and actuators as enabling technologies rather than the primary classification.

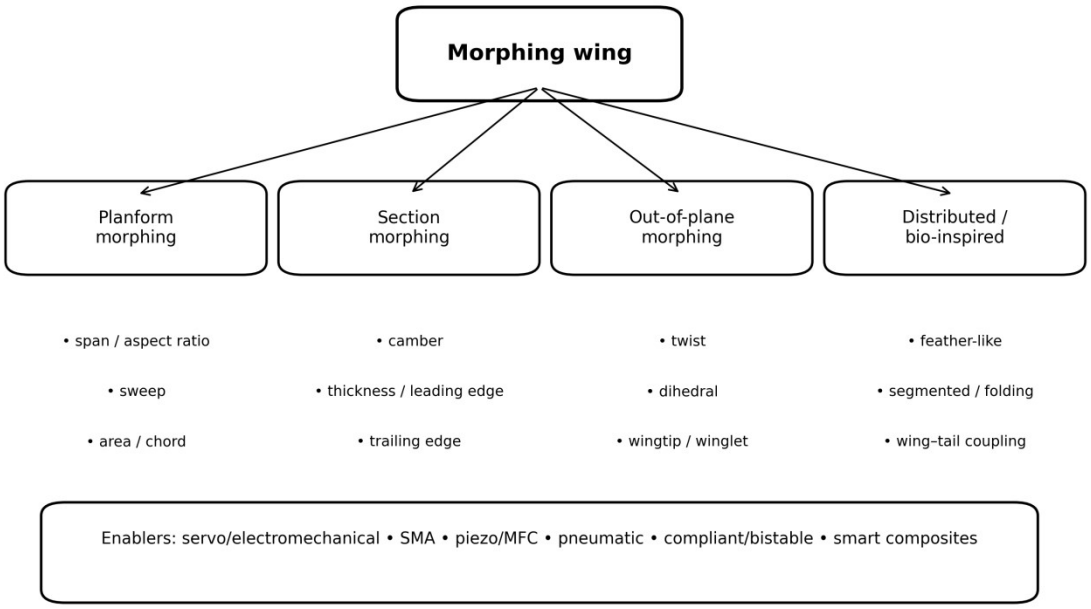

Figure 2. UAV morphing wing taxonomy organized by geometric degree of freedom

Planform morphing: span, sweep and area:-

Span and aspect-ratio morphing are among the most mature planform concepts. The Zigzag wingbox permits substantial span change and was designed specifically to combine the efficiency of a higher aspect ratio wing with the compactness and manoeuvrability of a shorter wing [13]. The GNATSpar concept demonstrated gear driven span morphing and wind tunnel validation [22], while the Transformer UAV extended the concept to symmetric and asymmetric span morphing using a rack and pinion mechanism [18]. The latter is particularly important because it demonstrates that a single morphing architecture can serve both mission adaptation and roll control functions.

The Transformer paper is also an important correction to the earlier manuscript. The approximately 5.5% endurance benefit is associated with the Zigzag wingbox study [13], not with the 2018 Transformer paper [18].

The Transformer study reported span extension up to 50% and experimentally investigated both symmetric performance morphing and asymmetric roll control [18]. Secondary literature reports 39.1% endurance and 9.1% range improvement under the stated constant lift coefficient comparison [18]; because these values are strongly condition dependent, they should not be generalized as universal UAV gains. A 2024 span extendable UAV investigation further reinforces the central net benefit issue: increasing span can improve aerodynamic efficiency, but the additional actuator and structural mass can reduce or eliminate the corresponding endurance benefit [39]. Thus, span morphing is best viewed as a mission optimization problem rather than a simple 'more span is better' rule.

Camber and airfoil-shape morphing:-

Camber morphing directly changes the pressure distribution and can therefore target hig -lift and low drag phases without a conventional discrete flap gap. Belt rib and compliant rib architectures replace hinge based deformation with distributed structural compliance [14]. FishBAC type and rear spar articulated systems further reduce mechanical discontinuities while maintaining useful camber authority. Communier et al. demonstrated a morphing camber system in a subsonic wind tunnel and showed that its drag benefit depended on operating lift coefficient [25].

AI assisted airfoil optimization is a more recent extension. The UAS S45 droop nose leading edge study used Black Widow Optimization coupled with CST parameterization and CFD validation; the optimized configurations produced up to 12.18% drag reduction, 15.22% lift todrag ratio improvement and approximately 10% improvement in the aerodynamic-endurance objective [29]. These are numerical aerodynamic results, not flight tested endurance gains, and should therefore remain classified as Level II evidence.

Twist, dihedral and wingtip morphing:-

Twist and wingtip morphing can redistribute lift, modify induced drag and provide direct lateral control authority. The Digital Morphing Wing demonstrated approximately ±10° spanwise twist and wind tunnel evidence of roll control benefits relative to a conventional rigid aileron [12]. Bio inspired feather like morphing has also demonstrated combined manoeuvrability and high speed drag management functions [15]. Recent twisting wingtip work indicates that morphing can influence divergence and flutter differently, highlighting the need to evaluate multiple aeroelastic modes rather than a single stability boundary [46].

Distributed and bio inspired morphing:-

Bio inspired concepts are valuable not simply because they imitate birds, but because they expose alternative ways to distribute deformation and control authority. Feather like segmented wings, avian wing tail coupling and albatross-inspired dynamic soaring morphing illustrate three distinct functions: local geometry management, coupled flight control, and exploitation of environmental energy. The 2025 review by Shahid et al. synthesized more than 296 bio inspired studies across aerospace and renewable energy applications, reinforcing the breadth of the biological design space but also demonstrating why UAV specific evidence stratification remains necessary [27].

Actuation, Materials and Structural Integration:-

Actuation is often the hidden determinant of whether a morphing concept is viable on a UAV. The mechanism must provide sufficient stroke and force while meeting strict mass, volume, and responsetime and energy constraints. Smart materials can reduce conventional actuator packaging, but they introduce their own limitations in thermal response, hysteresis, fatigue or stroke. Table 1 summarizes the principal trade-space.

Actuation class	Mass tendency	Response	Stroke	Energy / practical issue	Best fit UAV use
Servo/electromechanical	Medium	Fast	Large	Mature; gearbox and packaging mass	Span/planform morphing
SMA	Low	Slow moderate	Medium large	Thermal cycle, hysteresis, cooling and fatigue	Infrequent large deformation
Piezo/MFC	Very low	Very fast	Small	High bandwidth; limited displacement/output work	Camber, winglet and control surfaces
Pneumatic/inflatable	Medium	Moderate	Large	Air source / pressure system required	Large span or deployable structures
Compliant/bistable	Low	Fast or passive	Medium	Low part count; may be discrete/load-dependent	Low complexity morphing

Table 1. Actuation trade-space synthesized from the reviewed literature.

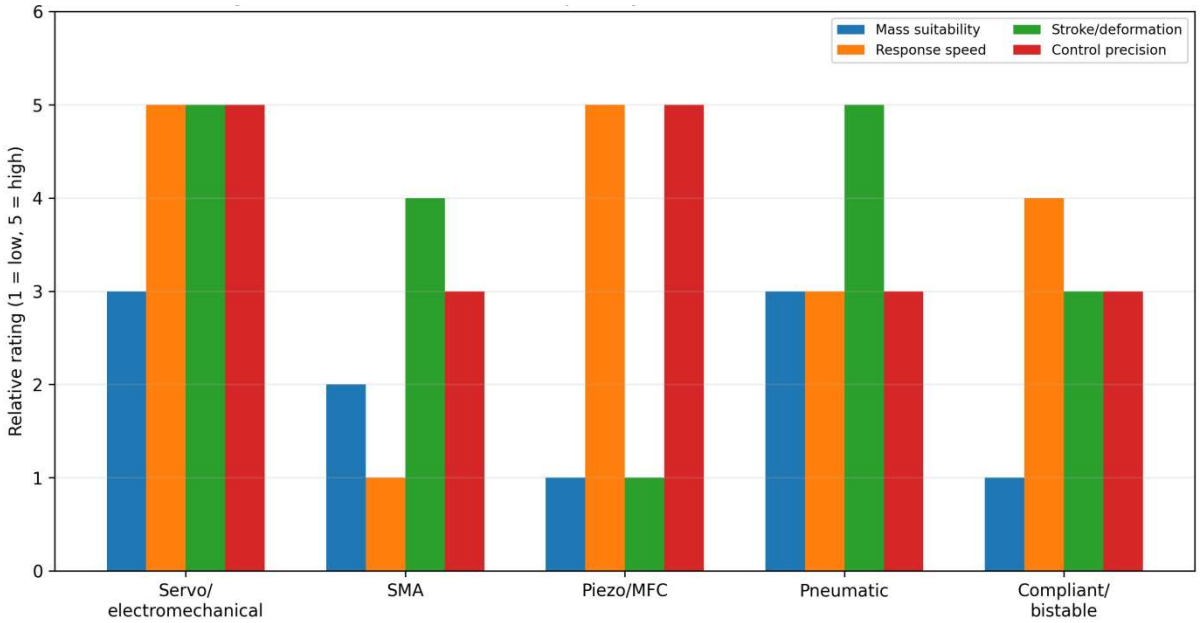

Figure 3. Relative actuator trade-space synthesized from the reviewed evidence; ratings are comparative, not measured universal properties.

Servo systems remain attractive because of their maturity and large stroke. SMA systems can be compact and lightweight but their thermally driven response and cycle life constraints can be severe [37, 54]. Piezoelectric/MFC systems offer very high bandwidth and low actuator volume; flight testing has shown faster response and lower velocity loss than a servo actuated baseline, although the available control authority can be smaller [51]. A high-actuation MFC bimorph architecture has subsequently demonstrated substantially increased output work and approximately ±12° actuator-driven morphing capability in a mini-UAVrelevant configuration [51]. The structural skin is equally important. Corrugated composites, lattice ribs, elastomeric skins and bistable laminates attempt to solve the flexibility stiffness conflict: the skin must deform repeatedly without excessive actuation force, yet remain aerodynamically smooth and sufficiently stiff under load [8, 9, 12]. This is one reason why morphing wings should be designed as integrated aero structural actuation systems rather than as an aerodynamic surface plus an actuator added afterward.

Aerodynamic Performance:-

Lift, drag and L/D:-

Across the reviewed studies, aerodynamic improvements of approximately 10 to 30% are common for selected metrics and configurations, but the values are not directly comparable. Span morphing primarily influences induced drag and aspect ratio; camber morphing is more effective when high lift is required; twist and wingtip morphing redistribute loading and can provide control authority; and distributed morphing can simultaneously modify pressure distribution and control moments. The correct comparison is therefore not a universal percentage but the improvement relative to the fixed baseline under the same Reynolds number, Mach number, lift coefficient and mission condition.

Dynamic morphing and stall:-

Periodic surface morphing adds an unsteady flow control dimension. Experiments at Reynolds number 50,000 using periodic MFC driven surface motion demonstrated suppression of a separated region, simultaneous lift increase and drag decrease, and delayed stall [50]. This is physically different from static shape optimization: the actuation frequency becomes a flow control parameter and can interact with shear layer instability. Such approaches are promising for low Reynolds number UAVs but require careful energy accounting because the actuation itself consumes power.

Low-Reynolds-number effects:-

Small UAVs commonly operate in a low to moderate Reynolds number regime, often below approximately 500,000 and, for micro and small UAVs, frequently below 100,000; these thresholds are used here as practical review ranges

rather than universal aerodynamic definitions, consistent with the low Reynolds number literature discussed below [48]. In this range, laminar separation bubbles, transition, surface roughness and manufacturing tolerances can strongly influence lift, drag and stall. Recent review work emphasizes that optimization should be organized around separation bubble physics and transition aware modelling rather than assuming fully turbulent flow [48].

Mission-phase matching:-

The aerodynamic function of morphing should be scheduled by mission phase. A practical architecture is high camber and/or increased area during take off and landing, intermediate geometry during climb, higher aspect ratio during cruise and loiter, and asymmetric span/twist or wingtip morphing for manoeuvre and control. This phase-matching concept is more defensible than treating morphing as a static optimization problem because it aligns the geometric degree of freedom with the dominant aerodynamic loss mechanism in each phase. Evidence balance check. Table 2 contains ten selected quantitative/evidence bearing studies. Three UAV studies report aircraft/mission or mission control outcomes (Zigzag wingbox, Transformer UAV, and wing tail morphing), while six UAV studies primarily report aerodynamic or aeroelastic outcomes. The albatross dynamic-soaring study [38] is retained separately as a transferable bio inspired mission/stability example rather than as a UAV evidence frequency count. This tally applies only to the selected studies in Table 2 and is not a frequency count for all 56 references.

Aircraft-Level Net Benefit:-

The most important synthesis of this review is that a morphing wing should be evaluated through a net benefit equation rather than a coefficient-improvement statement. A simplified endurance-oriented objective can be written as:

"Net mission benefit = aerodynamic benefit − actuator mass penalty − structural mass penalty − morphing energy penalty − reliability/control penalty"

The exact terms depend on propulsion type and mission. For an electric UAV, actuator energy directly competes with propulsion battery energy. For a fuel powered UAV, additional mass raises required power and changes the endurance calculation. The 2024 span extendable study is an instructive example because aerodynamic efficiency improved while actuator/structural mass constrained the whole-aircraft endurance benefit [39]. Conversely, the Zigzag wingbox showed that a heavier morphing wing could still deliver an endurance benefit under its design assumptions [13]. This leads to a general design rule: every published aerodynamic gain should be accompanied, where possible, by the added morphing mass, required actuation energy, duty cycle, and resulting aircraft level mission metric. Without those quantities, the engineering significance of a 10 to 20% change in L/D remains uncertain.

Aeroelasticity and Flight Dynamics:-

Morphing simultaneously changes aerodynamic loads, structural stiffness, mass distribution and control derivatives. The resulting aeroelastic problem has three distinct layers: static effects such as divergence and control reversal; dynamic effects such as flutter and modal coupling; and transient effects generated while mass, loads and geometry move during the morphing event. Ünlüsoy and Yaman demonstrated that morphing should be incorporated into aeroelastic tailoring from the conceptual stage because configuration changes can deteriorate flutter and divergence characteristics [42]. Recent biomimetic wing work similarly shows that high-fidelity structural and flutter models can reproduce benchmark modal and critical speed behaviour with useful accuracy [43].

Morphing rate is therefore a design variable, not merely an actuator specification. Slow configuration changes may be approximated by quasi steady aeroelastic models, whereas faster changes can introduce unsteady aerodynamic loads, transient structural excitation and time varying stability margins. The 2025 moving load study [47] illustrates why analysis should include the transition between configurations rather than only the pre and post morph steady states. The practical implication is that aeroelastic envelope protection should be implemented as a constraint layer around the morphing command. A conservative architecture can combine offline flutter/divergence maps with online estimates of airspeed, dynamic pressure, configuration and structural state; commanded amplitude and rate are then limited, scheduled or rejected when predicted margins fall below a verified threshold.

More advanced implementations may use reduced order models or uncertainty aware surrogates, but the safety logic should remain independently bounded. Aeroelastic analysis is therefore not a final certification step: it constrains allowable morphing amplitude, rate and flight envelope during conceptual design and real time operation.

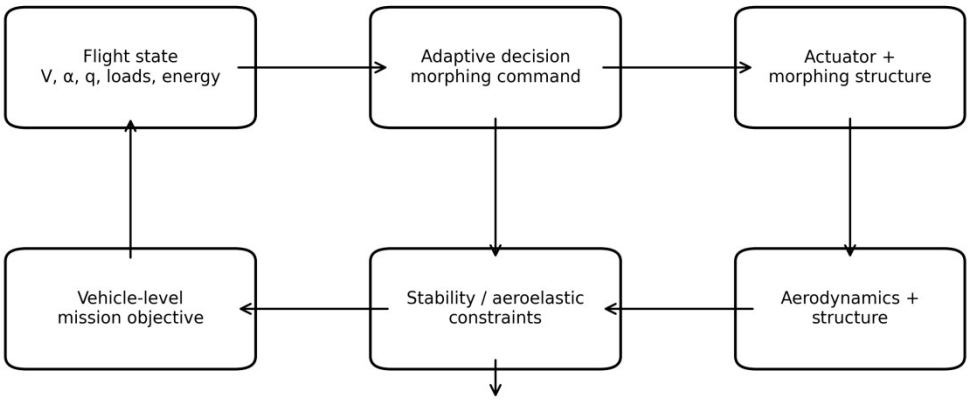

Figure 4. Deployment oriented integrated architecture linking flight state, morphing decision, actuator/structure, aerodynamics, aeroelastic constraints and mission objective.

The reviewed evidence supports a continuum of maturity rather than a binary 'AI versus non AI' distinction: (1) offline design optimization, where algorithms search geometry and actuation parameters; (2) offline surrogate-assisted schedule generation, where expensive aerodynamic/aeroelastic models are replaced or accelerated for design-space exploration; (3) online adaptive decision or control, where the vehicle updates commands using measured state; and (4) learning-enabled, fault tolerant flight control, where adaptation occurs under uncertainty while independently verified safety constraints remain authoritative. The literature is strongest at levels 1 to 2 and substantially less mature at levels 3 to 4.

AI, Optimization and Adaptive Control:-

Offline optimization:-

The most mature role of AI and optimization is offline design and schedule generation. Genetic algorithms, particle-swarm methods and other metaheuristics can search large shape spaces without requiring the vehicle to execute the optimization onboard. The UAS S45 Black Widow Optimization study is a representative example [29]. In practice, Bayesian or surrogate assisted optimization is especially attractive when CFD/FEA evaluations are expensive, while physics based parameterizations and differentiable models may further reduce search cost. The key deployment advantage is that the resulting geometry schedule can be validated on the ground and implemented as a lookup table or gain scheduled reference law.

Online adaptive control:-

Online morphing control is more demanding because the controller must account for changing aerodynamic, inertial and structural properties. A useful architecture separates three functions: (1) an inner shape control loop that tracks the commanded geometry; (2) a flight control and control allocation layer that distributes demanded forces and moments between morphing and conventional surfaces; and (3) a supervisory constraint layer that enforces actuator, structural and aeroelastic limits. Within this architecture, gain scheduling is attractive when the configuration space is well mapped, robust control is attractive when uncertainty bounds are known, and adaptive control is most useful when aerodynamic or structural parameters vary beyond those bounds. The 2024 control review [44] provides this broader context, while the 2024 drone study reporting approximately 2.5 times higher pull up pitch rate than elevator only control illustrates the potential value of coordinated allocation [32].

Surrogates and digital twins:-

Machine learning surrogates can reduce the computational cost of aerodynamic and aeroelastic prediction and support rapid optimization or digital twin functions. Their principal limitation is extrapolation: a model trained at one Reynolds number, morphing amplitude or structural state can become unreliable outside its training domain. Practical mitigation should therefore combine uncertainty estimation, physics constraints, out of distribution detection and fallback to conservative models. For onboard deployment, reduced order models are generally more

realistic than large unconstrained networks because latency, memory and verification burden matter alongside prediction accuracy. A useful digital twin should continuously compare model predictions with onboard measurements and degrade safely when confidence is insufficient.

Reinforcement learning and fault tolerance:-

Reinforcement learning is attractive for highly nonlinear morphing control because it can learn policies rather than fixed gain schedules. However, safety constraints, aeroelastic boundaries, actuator saturation and distribution shift make direct unconstrained flight deployment difficult. The practical pathway is hierarchical: a conventional robust stability controller and independently verified safety filter retain authority over the flight envelope, while an adaptive or learning layer optimizes morphing within that safe set. This distinction between performance optimization and safety critical stabilization is essential for credible flight deployment. The integrated architecture in Figure 4 should therefore be interpreted as a control allocation and envelope protection framework: mission objectives generate desired performance, the allocator selects combinations of conventional and morphing effectors, and the constraint layer filters commands against actuator, structural, aerodynamic and aeroelastic limits.

Quantitative Evidence Synthesis:-

Table 2 summarizes selected representative values retained from the reviewed studies. It is intentionally selective for quantitative comparability; Appendix A provides a full reference evidence map for all 56 numbered sources. Each quantitative value in Table 2 is presented with its study specific baseline and evidence level; the values should not be interpreted as pooled effect sizes.

Concept / study	Metric	Representative reported result	Baseline	Evidence	Year
Zigzag wingbox [13]	Mission	Up to 5.5% endurance benefit	Fixed span baseline	II / numerical/design analysis	2013
Transformer UAV [18]	Mission/control	Up to 50% span extension; 39.1% endurance and 9.1% range improvement under the study's stated comparison conditions	Fixed span configuration	III + V	2018
DNLE UAS-S45 [29]	Aerodynamic	12.18% CD reduction; 15.22% L/D improvement; ~10% aerodynamic-endurance objective improvement	Reference airfoil	II	2022
Wing–tail morphing [33]	Mission/control	Up to 11.5% energy-efficiency gain at 8–12 m/s	Non-morphing configuration	V	2024
Span-extendable UAV [39]	Aerodynamic + mission	Up to 15% aerodynamic-efficiency improvement; 6% CD reduction; whole-aircraft benefit constrained by actuator mass	Fixed rectangular wing	III/V	2024
Periodic surface morphing [50]	Aerodynamic	Large increase in L/D and delayed stall under tested low-Re conditions	Unactuated airfoil	III	2018
TWT morphing [46]	Aeroelastic	Up to 27.7% divergence-speed improvement, configuration dependent	Non-twisted wingtip	II	2025
Biomimetic flutter model [43]	Aeroelastic	<3% modal-frequency error and <2.1% critical-flutter speed error	Reference numerical models	II	2025

Concept / study	Metric	Representative reported result	Baseline	Evidence	Year
		against benchmarks			
Moving load UAV wing [47]	Aeroelastic	Demonstrates importance of transient moving load effects	Fixed/reference dynamic model	II	2025
Albatross dynamic soaring morphing [38]	Mission / stability	Morphing effects on stability and energy harvesting in dynamic soaring	Reference/non morphing configuration	II : numerical	2024

Table 2. Selected quantitative evidence retained from the reviewed studies.

Values are study specific, not pooled estimates; metric types, baselines, operating conditions, and evidence levels differ across studies and are not directly comparable. The albatross entry [38] is included as a mission/stability example; its evidence level follows the numerical treatment used in this review and should not be interpreted as a flight validation claim.

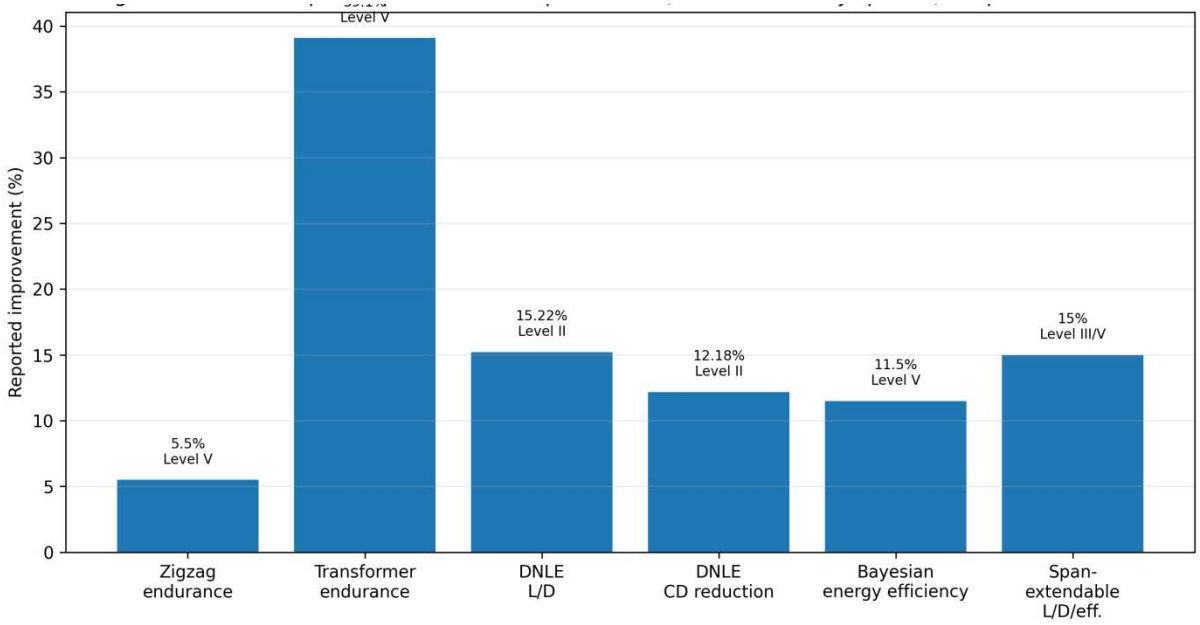

Figure 5. Selected reported performance improvements

Different baselines, operating conditions, and evidence levels do not compare the percentages directly as a statistical ranking. The revised synthesis supports three cautious conclusions. First, aerodynamic improvements of roughly 10 to 30% are repeatedly reported in selected configurations, but their transferability depends strongly on Reynolds number, baseline geometry and morphing amplitude. Second, mission-level benefits are less common and can be substantially smaller or even disappear when actuator and structural mass are included. Third, aeroelastic effects can be numerically large and are still much less frequently flight validated than aerodynamic effects. The evidence therefore favours a design philosophy in which mission-level and aeroelastic metrics are treated as first class outputs.

The qualitative ratings in Table 3 are intended as synthesis judgments rather than standardized certification scores. For example, camber morphing is rated High in aerodynamic maturity because the reviewed literature includes extensive wind-tunnel validation [25], while structural maturity remains Medium because skin fatigue and actuation integration remain active research areas [14, 52].

Technology Readiness and Deployment Barriers:

Technology	Aerodynamic maturity	Structural/actuation maturity	Flight evidence	Near-term UAV outlook
Camber morphing / FishBAC-type	High	Medium	Demonstrated	Medium to High
Span / planform morphing	High	Medium	Demonstrated on UAVs	Medium to High
Twist / wingtip morphing	Medium to High	Medium	Limited moderate	Medium
SMA morphing	Medium	Low to Medium	Mostly lab/bench	Low–Medium
Piezo/MFC morphing	Medium	Medium for small stroke	Demonstrated at small scale	Medium
Bio-inspired distributed morphing	Medium	Low to Medium	Selected flight demonstrations	Medium
AI offline optimization	High as design tool	High as software	Not a flight control requirement	High
AI online adaptive morphing	Emerging	Emerging	Limited	Low to Medium

Table 3. Qualitative deployment assessment synthesized from the reviewed evidence.

Ratings are authors' qualitative judgments based on three criteria: repeated aerodynamic demonstration, demonstrated structural/actuation functionality, and operational evidence. They are not literature derived numerical scores or formal TRL values. The most deployment ready technologies are those that use mature actuation and limit the morphing degree of freedom to a mission critical function. Camber and span morphing therefore appear closer to practical UAV adoption than highly coupled, continuously deformable architectures. Smart material systems are attractive where stroke and duty cycle are modest. AI is already useful as an offline design tool, but its transition to flight control requires verified models, uncertainty bounds, fault handling and aeroelastic safety constraints.

Research Gaps and Future Research Agenda:-

Gap 1: Net aircraft level benefit: Future studies should report added mass, actuation power/energy, duty cycle and the resulting endurance/range/payload benefit together with aerodynamic coefficients.

Gap 2: Standardized benchmark missions: The field needs common reference UAV geometries, Reynolds-number ranges, mission profiles and baseline definitions so that reported percentages become comparable.

Gap 3: Aeroelastic control integration: Morphing amplitude and rate should be optimized inside an aeroelastic envelope, not selected from aerodynamics alone.

Gap 4: Low Reynolds-number validation: Small UAV morphing should be tested at representative Reynolds numbers with transition aware CFD and wind-tunnel/flight validation.

Gap 5: Real time adaptive control: Research should move from offline optimization toward hierarchical, uncertainty-aware and flight validated adaptive controllers.

Gap 6: Reliability and fatigue: Long cycle morphing tests are needed for flexible skins, compliant ribs, SMA systems, MFC actuators and joints under realistic temperature and vibration environments.

Gap 7: Integrated digital twins: Future systems should combine aerodynamic surrogate models, structural state estimation, and actuator health monitoring and mission optimization in a single physics constrained framework.

Recommended research architecture:-

A practical next-generation morphing-UAV research programme should proceed in four coupled layers. Layer 1 is geometry and aerodynamic optimization; Layer 2 is structural and actuator co-design; Layer 3 is aeroelastic and flight-dynamics modelling; Layer 4 is constrained adaptive control and flight validation. Each layer should pass uncertainty and performance information to the next. This avoids the common failure mode in which an aerodynamically optimal geometry is discovered first and only later found to be too heavy, too flexible, too slow to actuate or aeroelastically unsafe.

Author Contributions:-

Author Contributions: Conceptualization and methodology were undertaken by all authors. Source screening and investigation, technical interpretation, and preparation of the manuscript were distributed among the co authors. Writing original draft and writing, reviewing and editing were undertaken by all authors. The corresponding author

coordinated the evidence framework, manuscript integration, and project administration. All authors reviewed and approved the final manuscript.

Limitations:-

This is a critical review rather than a formal systematic review. The revised manuscript makes the search logic, scope, eligibility rules and evidence coding procedure explicit, but the original project did not preserve database specific hit counts, duplicate counts, screening decisions, or inter rater records. Consequently, no retrospective PRISMA flow counts are presented as if they had been observed. This is a deliberate transparency safeguard rather than a claim of exhaustive database coverage. The review also does not pool heterogeneous percentages into a meta-analysis because the source studies generally use different Reynolds numbers, geometries, morphing amplitudes, baselines and performance definitions. The five level evidence hierarchy is an interpretive framework, not a validated formal quality scale.

Conclusions:-

Morphing wings offer UAV designers a powerful means of matching wing geometry to changing mission requirements, but the literature does not support a single universal performance-gain figure. The strongest evidence instead shows a conditional relationship between geometric freedom and mission benefit. Span morphing can improve induced-drag performance and simultaneously provide control authority; camber morphing is particularly effective for phase specific lift and drag management; twist and wingtip morphing can redistribute loads and augment control; and bio inspired distributed systems can combine multiple functions in a compact architecture. However, each additional degree of freedom introduces actuator, structural, control and aeroelastic costs.

The central engineering conclusion is therefore that morphing should be optimized at the vehicle level. Aerodynamic coefficients are necessary but insufficient. Added mass, actuation energy, response time, fatigue, stability and aeroelastic margins must be included in the objective and constraints. The literature also shows a clear maturity gradient: offline AI optimization is increasingly credible, while real time adaptive morphing control remains comparatively immature. The most promising path toward operational UAVs is a hierarchical architecture that combines mature low level flight control with constrained adaptive morphing, physics based or physics constrained surrogate models, actuator health monitoring and explicit aeroelastic limits.

Finally, the field would benefit more from standardized mission level experiments than from additional isolated CFD percentage improvements. Future studies should report a complete chain from geometry change to actuator burden, aerodynamic response, structural/aeroelastic response, flight control effect and final mission outcome. Such evidence would allow morphing wings to move from an attractive laboratory concept toward a quantitatively justified aircraft design technology.

Editorial verification note:

Reference [55] is bibliographically traceable and independently located, but its author metadata was retained exactly as verified from the available source. References [36] and [56] were completed from independently verified bibliographic information. No database hit counts or screening totals are fabricated retrospectively.

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