

Review

Mechanisms and Control Strategies for Morphing Structures in Quadrotors: A Review and Future Prospects

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Highlights

What are the main findings?

- Morphing UAVs employ diverse mechanisms including closed-chain linkages, bioinspired structures, and compliant materials, enabling versatile geometric adaptability.
- Control strategies such as reinforcement learning, sliding mode control, and model predictive control improve stability during dynamic morphology changes.

What is the implication of the main finding?

- Integration of morphing mechanisms with adaptive control expands UAV operational capabilities, supporting missions in confined spaces and critical applications like wildfire suppression.

Abstract

This review explores recent advancements in morphing structures for Unmanned Ariel Vehicles (UAVs), focusing on mechanical designs and control strategies of quadrotors that enable real-time geometric reconfiguration. Morphing mechanisms, ranging from closed-loop linkages to bioinspired and compliant structures, are evaluated in terms of adaptability, actuation simplicity, and flight stability. Control approaches, including model predictive control, reinforcement learning, and sliding mode control, are analyzed for their effectiveness in handling dynamic morphology. The review also highlights key morphing wing concepts such as GNATSpar and Zigzag Wingbox, which enhance aerodynamic efficiency and structural flexibility. A novel concept featuring an inverted slider-crank mechanism (ISCM) is introduced, enabling dual-mode UAV operation for both aerial and terrestrial missions, which is particularly useful in scenarios like wildfire suppression where stability and operation longevity are crucial. This study emphasizes the importance of integrated design approaches that align mechanical transformation with adaptive control. Critical gaps in real-world testing, swarm coordination, and scalable morphing architectures are identified, suggesting future research directions for developing robust, mission-adaptive UAV systems.

Keywords: morphing UAVs; shape-adaptive structures; reconfigurable mechanisms; adaptive flight control; aerial robotics



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1. Introduction

UAVs have been particularly helpful as aerial platforms in a variety of applications such as grasping operations [1], defense industry [2], surveillance and reconnaissance [3], precision agriculture [4], disaster monitoring [5], environmental mapping [6], infrastructure [7] inspection [8], logistics [9], and public safety [10]. In military contexts, UAVs play a critical role in intelligence gathering [11], target tracking [12], and combat operations [13]. In the commercial sector, they are increasingly adopted for tasks that require efficiency, access to hard-to-reach areas [14], or reduced risk to human personnel [15].

The growing importance of UAV technology lies in its potential to enhance operational efficiency, reduce costs [16], and improve safety [17] across diverse applications. Moreover, rapid advancements in artificial intelligence [18], communication systems [19], and battery technologies [20] are significantly expanding the capabilities and accessibility of UAVs, including their ability to dynamically alter geometry through morphing structures [21]. However, as morphing quadrotor designs evolve, several controversial and diverging hypotheses continue to shape the research landscape. For instance, while active morphing mechanisms promise improved maneuverability and multi-role adaptability [22], concerns remain about their added mechanical complexity [23], weight, and energy demands [24]. Similarly, debates persist regarding the viability of smart materials [25–27] as actuation alternatives, given their limited force output and integration challenges [28,29]. From a control perspective, reinforcement learning methods are emerging as powerful tools for handling nonlinear [30] morphing dynamics [31], yet their real-time applicability and reliability remain contested compared to classical model-based controllers such as Linear Quadratic Regulator (LQR) [1] or Model Referenced Adaptive Control (MRAC) [32]. These contrasting viewpoints underscore the need for further experimental validation and co-design frameworks that holistically address the interplay between structure, actuation, and control in morphing UAV systems.

The primary aim of this paper is to critically evaluate existing morphing mechanisms presented in the literature, with a particular focus on their transmission architectures and associated control strategies. By examining the mechanical design principles, actuation methods, and adaptive control frameworks employed in current morphing quadrotor platforms, this review seeks to identify both the strengths and limitations of prevailing approaches. This examination lays the groundwork for identifying future avenues of research from a control standpoint and morphing mechanism.

This paper is organized into five sections. Section 1 introduces the fundamental concepts and significance of morphing UAVs, outlining key debates in current research and highlighting future prospects. Section 2 provides a detailed review of existing morphing mechanisms in quadrotors, with particular focus on mechanical transmission architectures, actuation strategies, and integration with aerial functionalities. It also evaluates various control frameworks, such as model-based and learning-based approaches used to manage the dynamic challenges introduced by in-flight reconfiguration. Furthermore, Section 2 analyzes the methodologies employed in previous studies, including modeling techniques, experimental validations, and control-performance assessments, while also identifying current limitations and emerging opportunities in morphing UAV control. Section 3 discusses the trends, limitations and gaps along with an introduction of a novel conceptual design enabling dual-mode UAV operation, offering a potential solution for rapid wildfire intervention through increased stability and mission endurance. Section 4 provides the conclusions and outlines key unresolved challenges in morphing quadrotor research, including the need for advanced modeling frameworks, robust control under configuration changes. Section 5 includes patent information, author contribution and acknowledgements.

2. Morphing and Control of Structures for UAVs

This review investigates morphing quadrotor and UAV technologies through a structured analysis of recent literature, with a primary emphasis on mechanical morphing mechanisms and associated flight control strategies. Although, there are exclusive reviews [21] on morphing UAVs, the need for a critical evaluation of a drive system of a morphing mechanism necessitates a new review paper with a different perspective on the subject. The reviewed studies were selected based on their relevance to UAVs capable of geometric shape changing, published between 2015 and 2025 in peer-reviewed journals and leading robotics conferences. In terms of mechanical design, the methodology focuses on categorizing morphing mechanisms into key types—including variable-length arms, foldable or tilting rotor systems, and bioinspired multi-link configurations—and analyzing their actuation approaches such as servo motors, linear and smart actuators. Simultaneously, the review evaluates control methods employed to maintain flight stability during morphing operations, including adaptive control, sliding mode control, MRAC, and Deep Reinforcement Learning. For each source, key parameters such as reconfiguration range, structural complexity, controller responsiveness, and experimental validation are extracted and comparatively assessed. This methodological framework enables a critical synthesis of state-of-the-art morphing UAV technologies, forming the basis for identifying their performance trade-offs and for the development of next-generation multi-modal aerial platforms.

2.1. Mechanism for Morphing

We classify the mechanisms with closed-chains in Section 2.1.1. However, the open-chain mechanisms are mentioned in Section 2.1.2.

2.1.1. Closed-Chain Mechanisms for Morphing UAVs

Closed-chain mechanisms in morphing UAVs, such as four-bar linkages, Sarrus linkages, and parallelogram-based structures, offer symmetric and coordinated transformations that enhance flight stability and control precision. These mechanisms typically require fewer actuators, enabling compact and lightweight designs while maintaining balanced inertia during morphing. Their deterministic motion paths simplify kinematic modeling and facilitate integration with control systems, making them ideal for applications requiring rapid, reliable, and structurally consistent reconfiguration during flight.

The FOLLY quadrotor [33] introduces a well-engineered, fully autonomous morphing mechanism based on a four-bar crank-rocker system driven by a single servo motor and spur gears as shown in Figure 1, enabling rapid folding and deployment of its arms in just 0.6 s. This design achieves a 62.65% reduction in volume, significantly enhancing portability while maintaining flight stability. The mechanism's effectiveness is validated through detailed kinematic and dynamic analysis, supported by simulations and experimental testing. The choice of acrylic as a frame material offers a balance between costs, vibration damping, and structural integrity. Overall, the system demonstrates a practical and efficient solution for pre- and post-flight reconfiguration in UAVs.

The Skygauge drone features a patented morphing mechanism centered around a sophisticated thrust-vectoring architecture, employing four independent two-degree-of-freedom spherical actuators located at each rotor hub [8]. Unlike traditional multirotor drones that rely on fixed-axis thrust, Skygauge's design allows each rotor to pivot in both pitch and yaw, enabling precise manipulation of thrust vectors in real time as shown in Figure 2. This configuration allows the drone to maintain a stable fuselage while dynamically adjusting its orientation and contact force—making it particularly well-suited for contact-based industrial inspections such as ultrasonic thickness testing, where stability, precision, and force control are

critical. The drone initiates inspection with a “contact mode” that is guided by forward-facing LiDAR to approach surfaces at a controlled velocity. An onboard system dispenses ultrasonic couplant just before contact, while an integrated force sensor delivers real-time feedback. The system then continuously adjusts the rotor thrust vectors to maintain a consistent and perpendicular contact force, even on curved or irregular surfaces. As a result, Skygauge can conduct stable inspections across a 360° range, including challenging orientations such as sloped roofs, cylindrical tanks, ship hulls, and underside structures—areas that are difficult or impossible to reach using traditional UAVs.

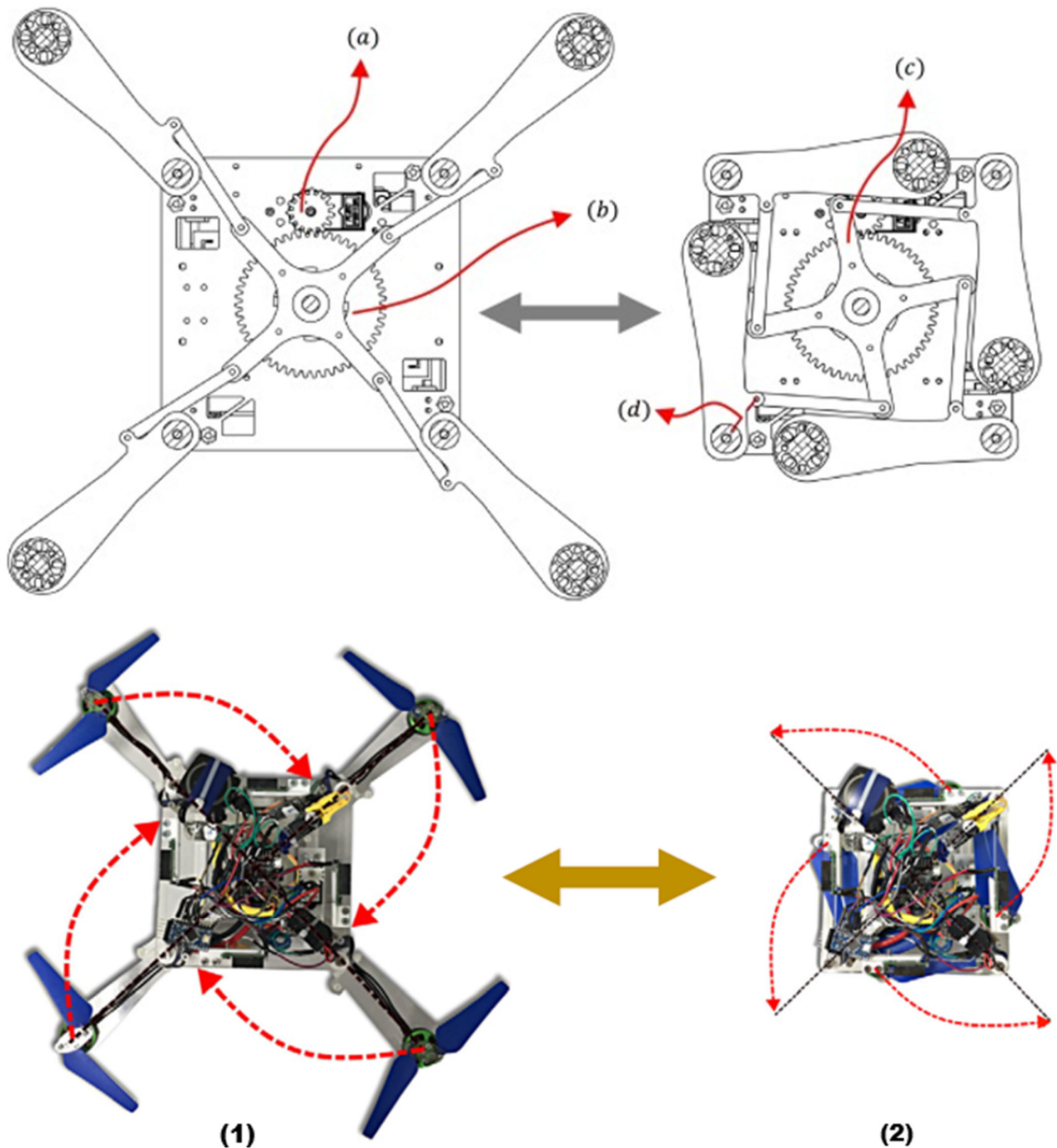


Figure 1. The illustration of morphing mechanism of FOLLY designed in the form of four symmetric crank-rocker mechanisms which is driven by only one servo with spur gear (a) and transmitted through crank (c) attached spur gear to the rocker (d) jointed on the frame (b), (1) Deployed, (2) Folded [33].



Figure 2. Morphing mechanism of Skygauge: (a) configuration for forward motion, (b) configuration for backward motion [8].

However, the technical sophistication of Skygauge comes with trade-offs that limit its feasibility for broader applications. The drone relies on a total of 16 motors: eight high-performance brushless motors that drive the coaxial propellers and eight servo motors that enable the vectoring motion of each rotor. This motor-rich architecture increases the complexity, weight, and power consumption of the system. To sustain adequate flight duration and torque control, a significantly larger battery is required, which further constrains the drone's payload capacity and operational endurance. Additionally, the use of multiple actuators adds to the system's mechanical and maintenance overhead, making it less suitable for lightweight, long-range, or swarming UAV applications where energy efficiency and minimalism are crucial. While the Skygauge is highly effective in its niche—delivering stable, precise, and repeatable contact in GPS-denied and confined environments—its current design is not optimized for tasks requiring high payload delivery, extended flight times, or rapid deployment over large areas. Therefore, while it represents a cutting-edge advancement in aerial inspection robotics, its practicality remains limited to specialized missions rather than general-purpose UAV operations.

The Sarrus linkage-based morphing mechanism [23] offers a compact yet robust approach to in-flight reconfiguration, significantly enhancing the UAV's adaptability in constrained environments. The core innovation lies in the integration of a symmetrical four-sided Sarrus linkage with two coplanar parallelogram four-bar linkages per limb, achieving synchronized linear extension and retraction of all four rotor arms through a single degree of freedom as shown in Figure 3. This contrasts with many prior morphing designs that rely on multiple actuators, often complicating control and introducing structural asymmetry. The choice of the Sarrus linkage allows the quadrotor to change its overall size by more than 23%, enabling it to navigate through confined spaces without altering the rotor orientation, thus maintaining aerodynamic and dynamic stability during flight. From a dynamical systems perspective, the mechanism ensures minimal disturbance to the moment of inertia during transformation due to its symmetric architecture, and the cascade PID controller successfully compensates for its geometric transitions in real time. Experimental validations—particularly the in-flight morphing through a narrow carbon fiber frame—demonstrate not only feasibility but also high trajectory accuracy, making this morphing strategy highly suitable for rescue, exploration, and indoor navigation tasks. The design also represents a compelling step toward autonomous, environmentally adaptive aerial robots capable of geometry-based mission optimization.

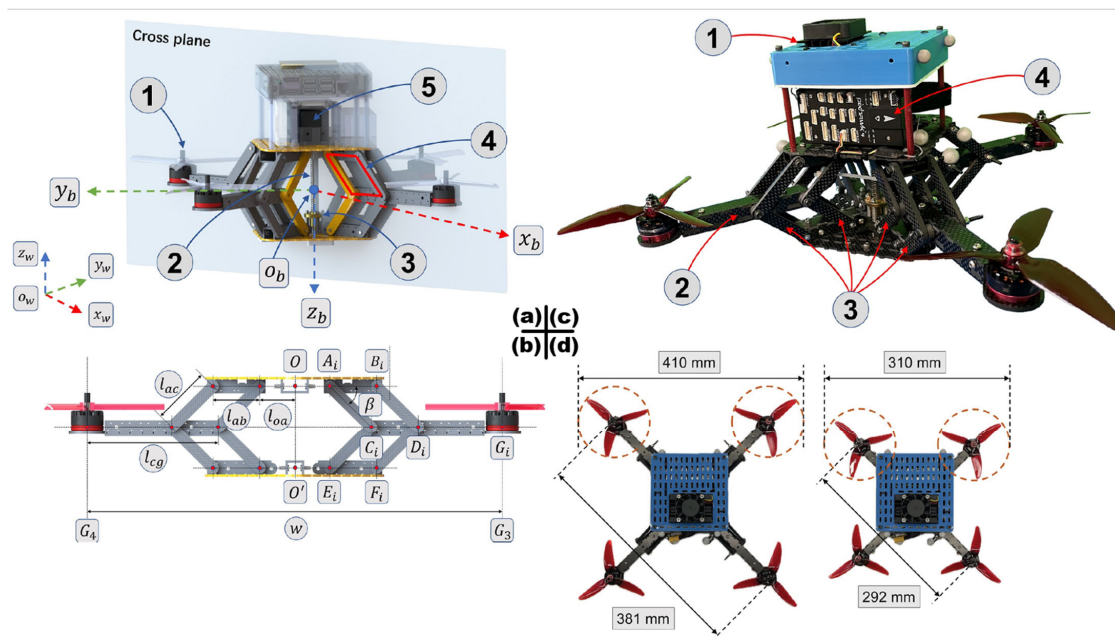


Figure 3. The Sarrus linkage-based morphing mechanism; (a) The cross plane of the morphing mechanism showing servo motor with propeller (1), arm of the quadrotor (2), lead screw (3), four-bar parallelogram linkage (4), and servo motor (5), (b) Design parameters and joints, (c) Isometric view of The Sarrus linkage-based morphing mechanism, (d) The change in distance between propellers [23].

The MorphoCopter in Figure 4 has an exceptionally well-balanced morphing mechanism, featuring a single actuated rotary joint transmitted through a robust 4-bar linkage that allows its twin-arm frame to transition smoothly between a standard X-shaped quadrotor and a compact stacked bicopter form, reducing its width by nearly 70% (from 447 mm to 138 mm) [34]. This design adeptly addresses the common trade-off in morphing UAVs, providing significant dimensional adaptability while preserving full control authority across all configurations with just one servo actuation. The inclusion of fixed inward propeller tilts cleverly mitigates the loss of roll leverage in narrow forms, converting reaction torque into usable control moments, and enabling maintainable attitude control even when traditional thrust arm leverage vanishes. Overall, the MorphoCopter provides advantages primarily for one-dimensional transformations and exemplifies a tightly integrated morphing UAV platform where mechanical simplicity, dynamic adaptability, and control sophistication combine to achieve high-performance shape-shifting flight.

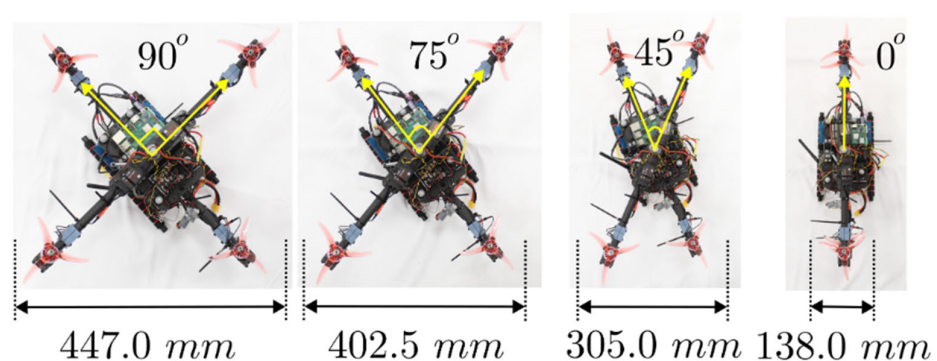


Figure 4. Geometry change capability of MorphoCopter [34].

A biomimetic design paradigm was exemplified by a morphing mechanism, closely modeled after the kinematics of an eagle's claw during prey capture as shown in

Figure 5a [24]. Mechanically, the quadrotor utilizes a closed-loop multilink frame structure comprising 20 articulated parallel links, including claw links, middle connectors, outer links, and motor bases. A single central servomotor actuates the entire morphing process through a synchronized gear-rack system, enabling simultaneous vertical folding of all four arms as shown in Figure 5b. What differentiates this mechanism is its ability to maintain constant propeller orientation across all morphing configurations, thanks to the integration of parallelogram-based linkages. This design ensures flight stability during dynamic transitions, addressing a common challenge in 3D morphing UAVs. The morphing capability extends beyond simple shape change; it facilitates real-time adaptive grasping and perching by emulating the biological actuation of an eagle's claws. The morphing range is smooth and continuous, allowing in-flight transitions, and is further enhanced by a controller that regulates servo torque during contact with objects of unknown size. Altogether, the mechanical design demonstrates both structural elegance and practical versatility, making it a significant advancement in morphing aerial robotics.

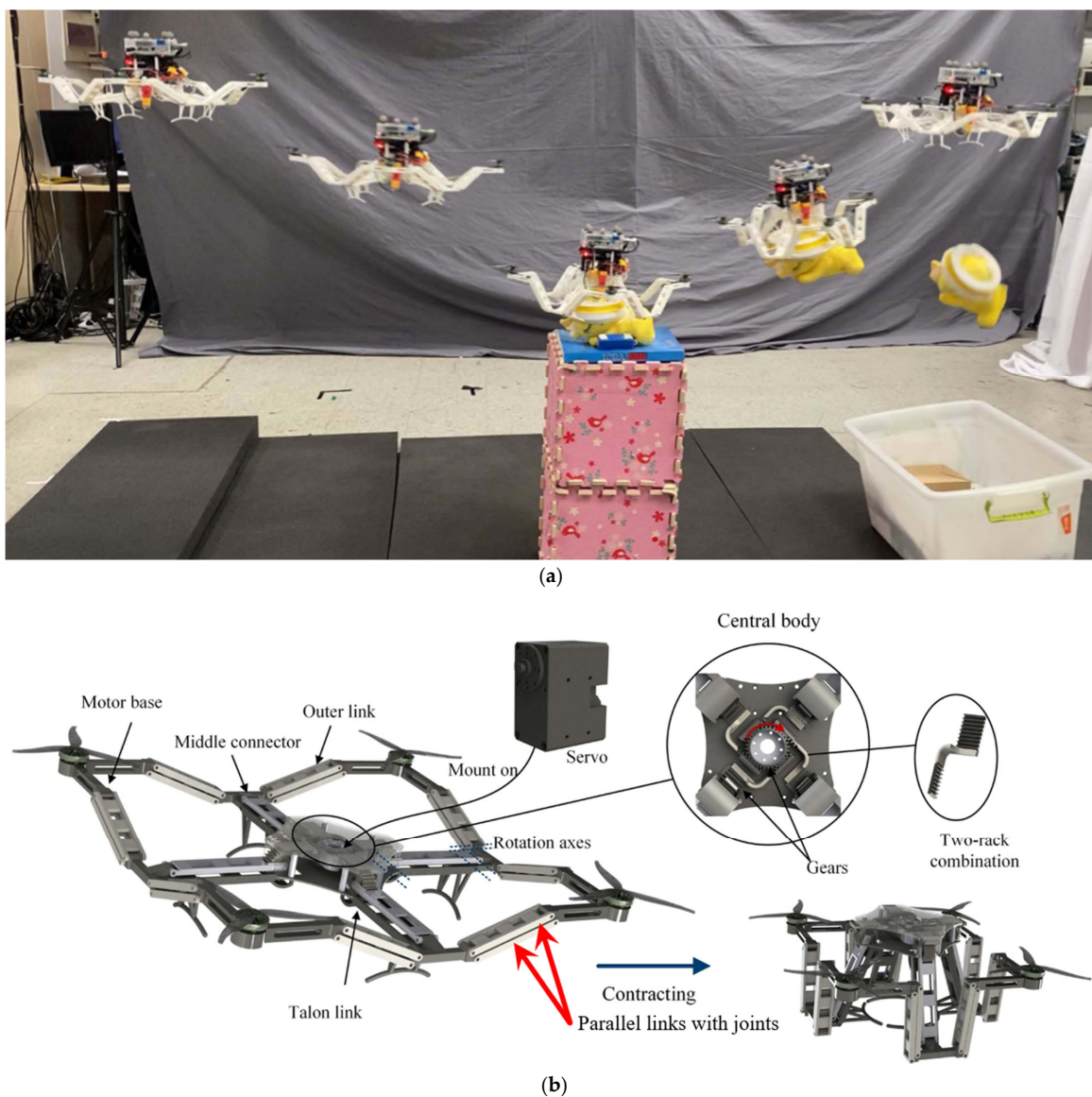


Figure 5. Biomimetic design of morphing quadrotor; (a) dynamic grasping operation, (b) parallel mechanism of morphing quadrotor [24].

The X-Morf quadrotor introduces a unique morphing concept by dynamically adjusting its X-geometry during flight through an actuated scissor joint mechanism between two tandem-rotor arms. Unlike many foldable or reconfigurable drones that rely on passive or pre-defined configurations, X-Morf actively alters its arm angle in its mid-flight by use of four bar linkage assembled with a scissor joint at the intersection of the arms as shown in Figure 6, achieving up to a 28.5% change in span within 0.5 s [35]. This morphing not only enhances the drone's adaptability in cluttered environments—enabling it to reduce its footprint to pass through narrow gaps—but it also poses complex dynamic challenges due to the induced variations in inertia and center of mass. The morphing capability has been further reinforced by a magnetic docking mechanism that enables crash resilience, allowing the upper arm to detach upon impact, preserving structural integrity. Overall, the X-Morf exemplifies an innovative and practical realization of in-flight morphing in quadrotors, bridging the gap between adaptive geometry and stable control performance for next-generation aerial robotics.

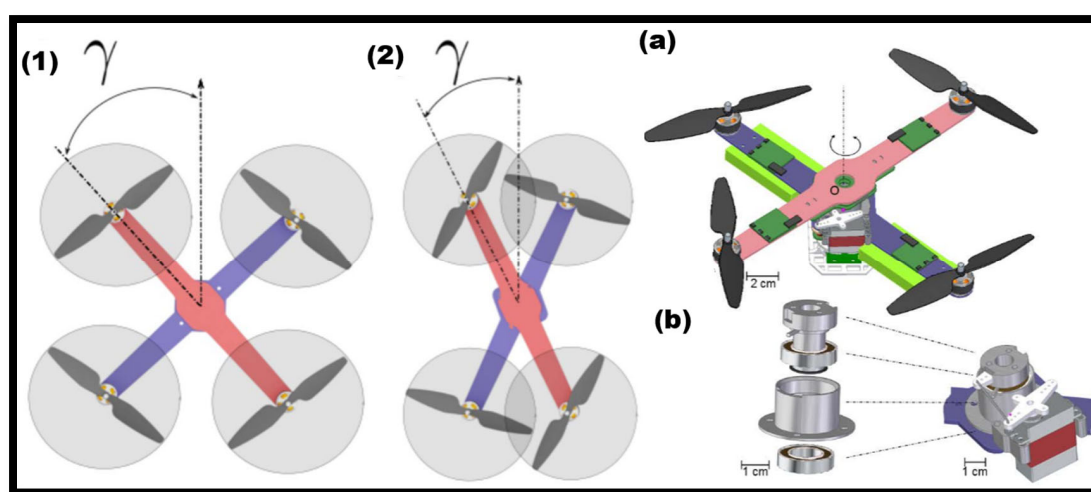


Figure 6. X-Morf; (1) Unfolded state, (2) Folded state, (a) The CAD model of X-Morf, (b) The scissor joint and its actuation mechanism [35].

2.1.2. Open-Chain Mechanisms for Morphing UAVs

An open-chain mechanism is a type of kinematic chain in which the links are connected end to end without forming a closed loop. Each link is joined to the next through a joint, typically allowing relative motion such as rotation or translation. These mechanisms are common in robotic arms, cranes, and manipulators, where movement starts from a fixed base and propagates through each link to the end-effector. Open-chain mechanisms are relatively easy to analyze and control, offering high flexibility and a wide range of motion. However, they are generally less structurally rigid than closed-chain mechanisms and more susceptible to accumulated errors along the chain.

The Multi-Modal Mobility Morphobot (M4) presents a significant advancement in morphing robotics by leveraging appendage repurposing to achieve exceptional locomotion plasticity across diverse terrains and mission scenarios [36]. Unlike traditional multi-modal robots that rely either on a high number of single-function appendages or simple shape-morphing strategies, M4 combines morpho-functionality and redundancy manipulation within a unified, scalable architecture as shown in Figure 7. Each of its four limbs can be dynamically transformed into wheels, legs, or thrusters, enabling eight distinct locomotion modes such as flying, rolling, tumbling, crouching, and balancing by the help of four motors assembled on each arm of quadrotor as shown in Figure 7B. This versatility allows M4 to adapt to complex environments such as steep slopes, collapsed structures, or low-

ceiling pathways by autonomously selecting the most suitable mode. M4's design is further enhanced through integrated onboard sensing, optimization-based control algorithms, and a multi-modal probabilistic roadmap for autonomous path planning. Experimentally validated capabilities, such as wing-assisted incline running, obstacle tumbling, and scout-like standing illustrate not only its mechanical dexterity but also its high potential in critical applications like search and rescue and space exploration. Overall, M4's design exemplifies a novel paradigm where the repurposing of shared, multifunctional components directly enables superior adaptability and autonomy.

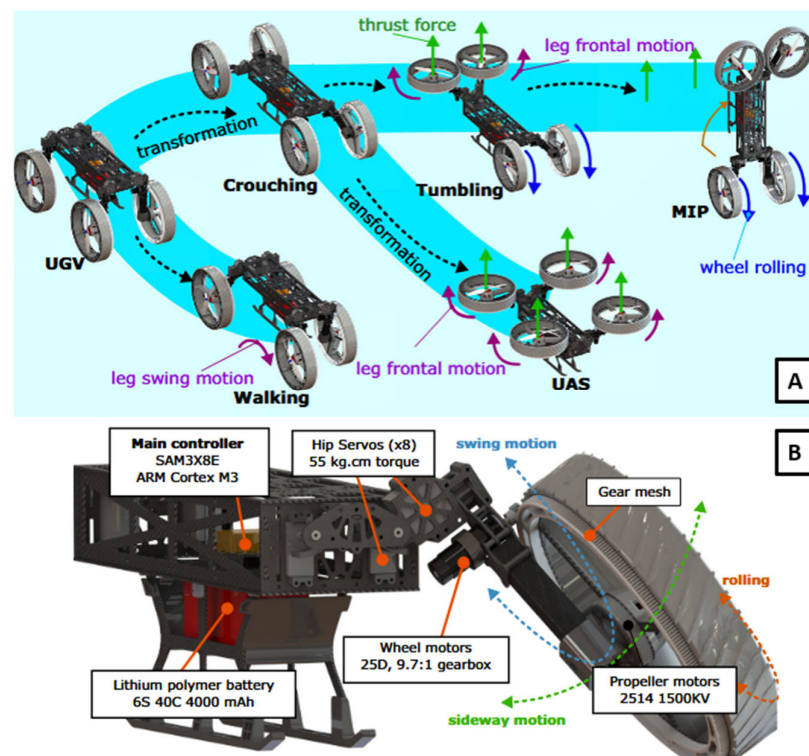


Figure 7. M4; (A) various morphing capabilities, (B) The actuators for morphing [36].

A comprehensive engineering-oriented analysis of avian flight offers valuable insights for the development of morphing UAVs [37]. This work systematically translates the morphological and aerodynamic characteristics of bird wings into analytical models that can be used for the design of flapping and morphing aerial platforms. Notably, the implementation of a simplified two-joint arm model to represent wing kinematics enables the replication of complex motions such as spanwise twist, dynamic sweep, and camber variation which are key features for enhancing aerodynamic adaptability in morphing UAVs. The study also highlights the significance of unsteady aerodynamic mechanisms, particularly leading-edge vortices, which are essential for maintaining lift at low Reynolds numbers typical of small-scale UAV operations. Through the integration of high-resolution geometric data, motion capture techniques, and computational fluid dynamics simulations, the paper establishes a rigorous foundation for bioinspired morphing wing design. This engineering perspective not only bridges biological understanding and flight mechanics but also facilitates the systematic development of high-performance, adaptive UAV architectures.

The sliding arm quadrotor [38] represents a significant advancement in UAV adaptability through dynamically adjustable structural parameters. Unlike traditional morphing designs that rely on passive reconfiguration or fixed morphologies, this approach actively varies the quadrotor's arm lengths during flight using servo-driven sliding mechanisms, thereby altering the moment of inertia and center of gravity in real time. This structural actuation is integrated

into the attitude control loop, enabling precise control through both rotor speed modulation and shape variation. The continuous morphing capability enhances fault tolerance—allowing flight even in propeller failure scenarios—and improves maneuverability, particularly in large multirotor platforms where conventional motor mixers are insufficient. Simulations demonstrate the UAV's ability to follow complex trajectories and waypoint navigation solely through shape change, confirming its potential for advanced control and disturbance rejection. This active morphing strategy not only broadens operational envelopes, but it also lays groundwork for intelligent aerial platforms with embedded structural autonomy.

A tiltable-rotor system is implemented in the Voliro omni-orientational hex-copter [39]. This mechanism shown in Figure 8 enables each of the six rotors to rotate independently around their arm axes, allowing full control over the direction of thrust vectors. Unlike conventional multirotor with fixed rotor orientations, the Voliro design decouples position and orientation control by dynamically adjusting both the rotor speeds and their tilt angles. This design results in its omnidirectional maneuverability—the UAV can fly in any direction while maintaining an arbitrary orientation in 3D space. The main benefits of this morphing architecture include increased agility, improved energy efficiency (due to reduced internal counteracting forces), and the ability to perform complex tasks, such as wall interaction, inverted flight, and precise pose holding during contact-based inspection. The system demonstrates its capabilities through experiments such as stable upside-down hovering and controlled surface movement, showcasing its superiority over traditional multirotor platforms in both mobility and interaction potential.

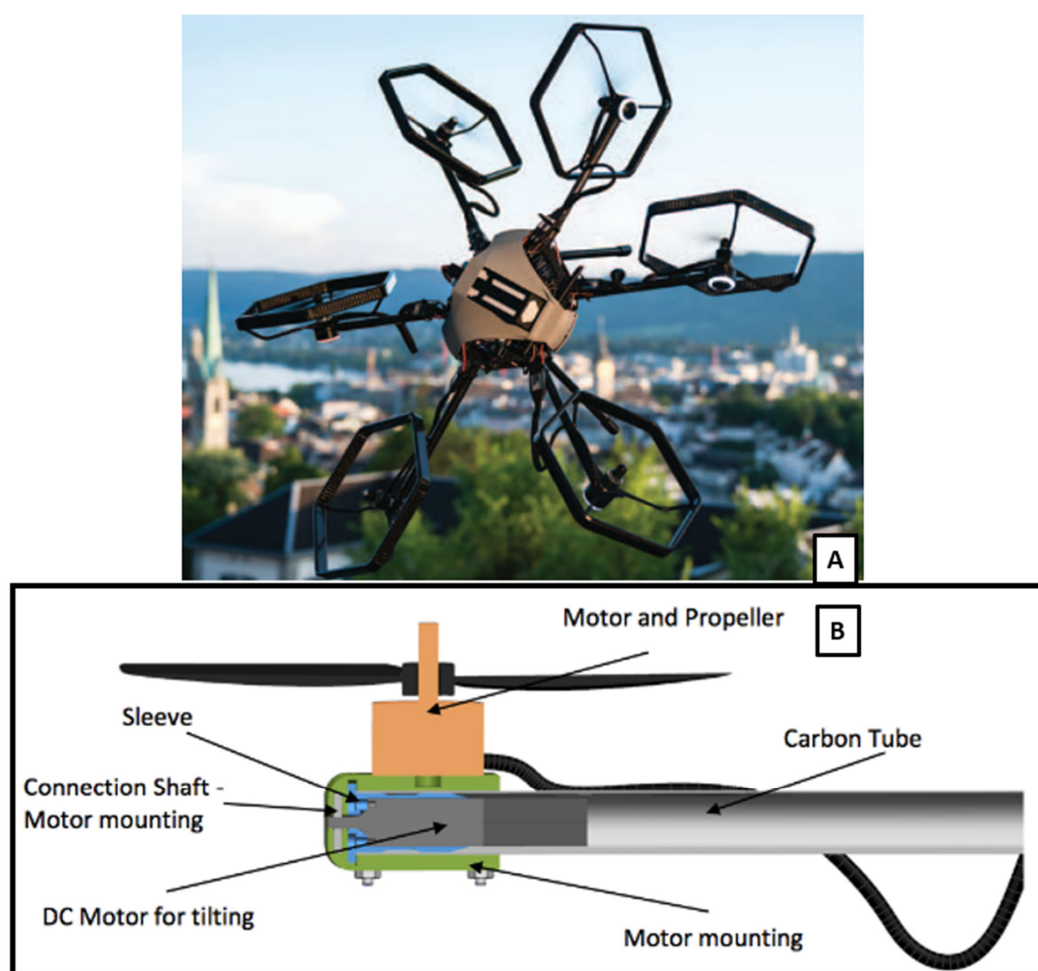


Figure 8. Voliro: (A) Omniorientational configuration; (B) The morphing mechanism [39].

SOPHIE presents a pioneering morphing mechanism by introducing an UAV fabricated entirely from soft, flexible Thermoplastic Polyurethane material, enabling full-body shape adaptation through tendon-actuated arm deformation [40]. Unlike conventional UAVs with limited morphing, SOPHIE's flexibility is structurally embedded, allowing in-flight adaptation and perching without extra mechanisms as shown in Figure 9. Its shape is controlled by variable infill density during 3D printing, affecting elasticity and flight dynamics. A quasi-static model links morphing-induced deflections to control inputs, ensuring stability. The study shows that controlled flexibility enhances capabilities like complex surface landings, though extreme softness demands advanced learning-based control.

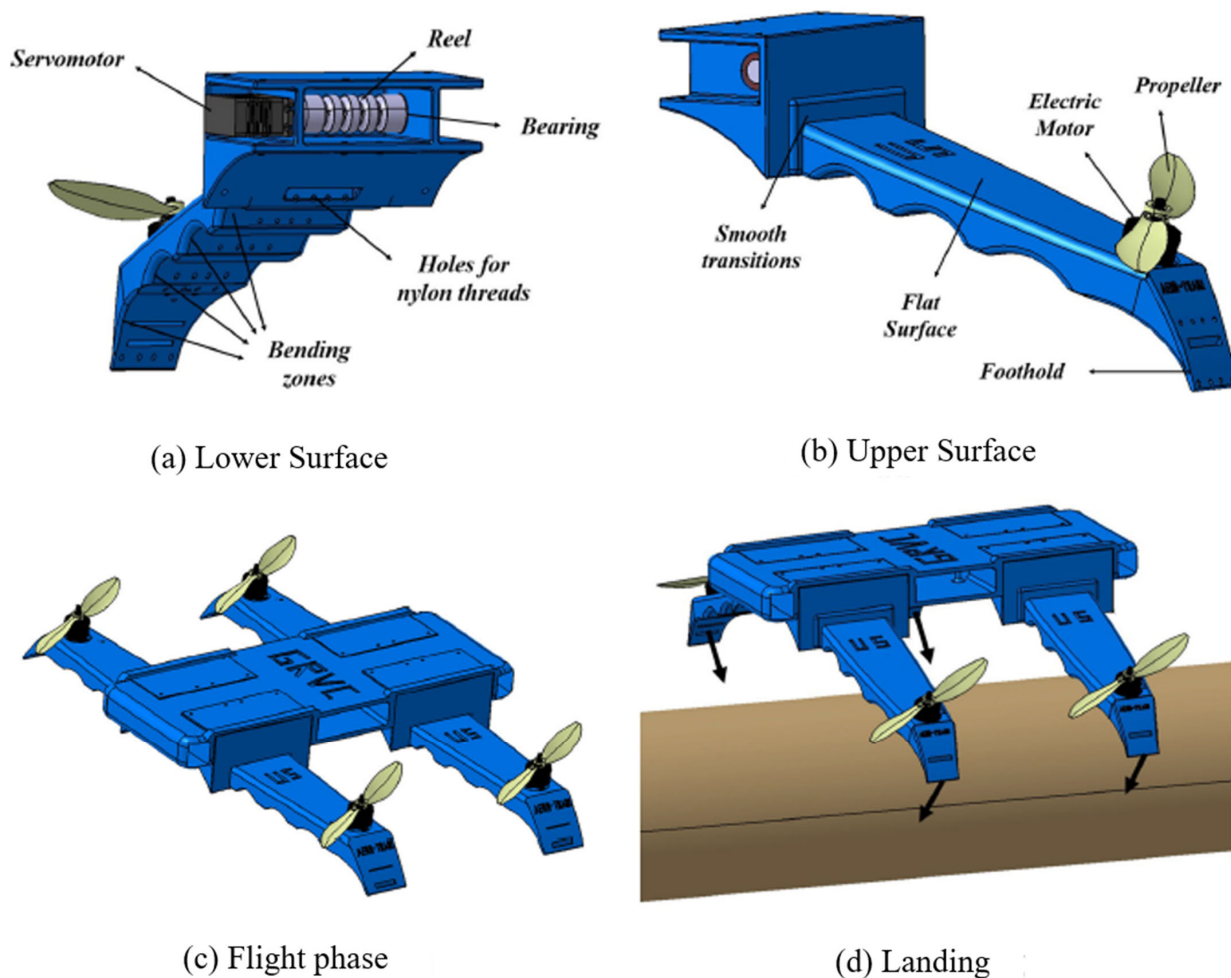


Figure 9. Morphing mechanism of SOPHIE: (a) the structure for grasping and morphing arm driver; (b) the propeller on morphing arm; (c) the case of flight of SOPHIE; (d) the case of landing of SOPHIE [40].

The Ring-Rotor presents a novel and efficient morphing mechanism within the quadrotor UAV domain by introducing a retractable, ring-shaped structure capable of simultaneously adjusting its both length and width with a single servo actuator. Unlike traditional morphing designs that rely on multiple actuators or complex variable-arm configurations, this mechanism uses a string-and-spring-based passive retraction system shown in Figure 10 that ensures uniform morphing behavior while preserving a square geometry [22]. This simplification reduces system complexity and weight, enabling its practical adaptation to spatial constraints, such as narrow gaps or holes, without the need for external manipulation or reorientation. Additionally, the ring configuration frees up the central space, allowing for whole-body aerial grasping without added robotic arms transforming

the morphing mechanism into both a structural and functional innovation. Overall, the mechanism reflects an elegant convergence of mechanical minimalism and high morphing utility in UAV applications.

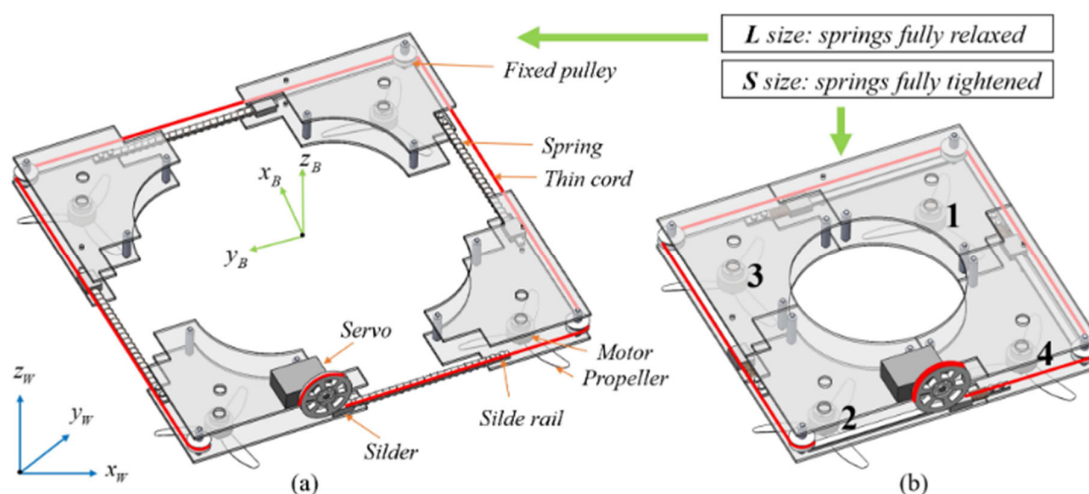


Figure 10. The two case of the Ring-Rotor: (a) Extended case; (b) Contracted case [22].

Quadrotor-Blimp With Balloon exemplifies a highly adaptive structural design that enables functional transformation between two flight modes—blimp and quadrotor—based on situational demands [41]. The Janus platform employs a novel mechanically triggered transition system, in which each motor arm rotates 90° via a reel and clutch system when balloon failure is detected, effectively converting the propulsion configuration from horizontal (blimp) to vertical (quadrotor). This morphing transition is both rapid and mechanically elegant, facilitated by lightweight elastic strips and a fishing-line tension mechanism as shown in Figure 11. This design has the ability to perform such a transformation autonomously within 0.362 s after failure detection, which is initiated by a multi-sensor fusion algorithm integrating piezoelectric, proximity, and accelerometer data. The mechanism is not only structurally efficient—with minimal added mass—but is also highly responsive, enabling mid-air stabilization via a nonlinear geometric flight controller. Overall, the morphing mechanism’s seamless integration with sensing and control systems offers a compelling solution for resilient aerial platforms operating in unpredictable environments.

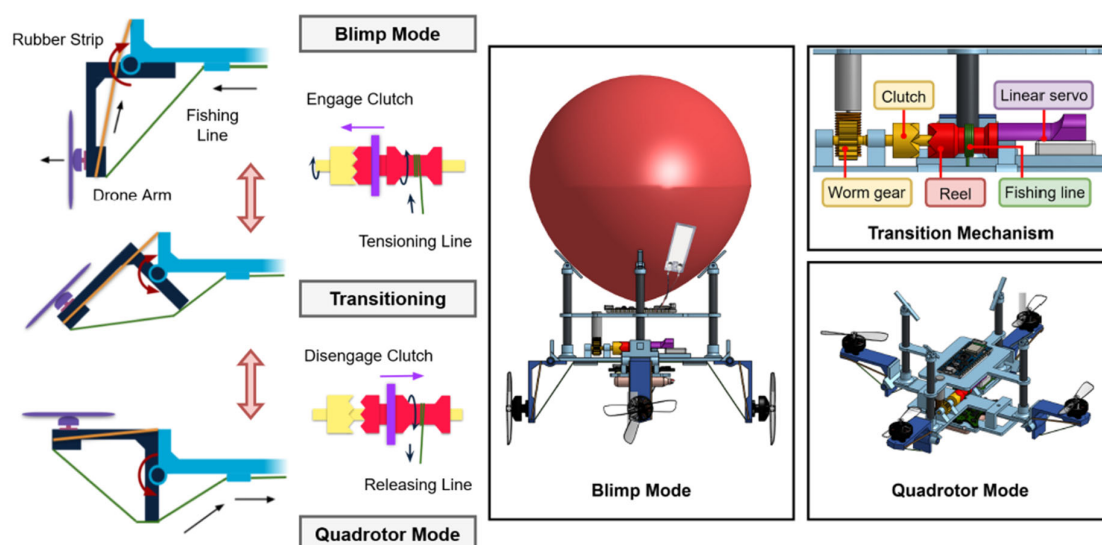


Figure 11. Morphing mechanism of Quadrotor-Blimp With Balloon [41].

Unlike traditional fixed-frame quadrotors, novel design allows each of the four arms to rotate around hinges and it assumes non-coplanar configurations, enabling overlap and drastic width compression by reducing the diameter of a single rotor [31]. This functionality permits the UAV to navigate through extremely narrow gaps, a critical advantage in cluttered or constrained environments. From a mechanical standpoint, the morphing capability introduces significant changes in the center of gravity, moment arms, and inertial properties, which are dynamically accommodated by an extended-state reinforcement learning controller. The system effectively computes real-time mass distribution and applies a fast simplex algorithm to manage control allocation, demonstrating reliable flight stability even during active transformation. This fusion of mechanical innovation and intelligent control marks a significant advancement in morphing UAV technology.

QuadPlus introduces a novel morphing mechanism that distinguishes itself from conventional shape-morphing drones by enabling extensive thrust vectoring through independently controlled biaxial tilting of each propeller [42]. This functionality allows the QuadPlus to decouple attitude and position control an essential capability for high-agility operations in constrained environments. Mechanically, the design achieves up to 100° and 180° rotation about the lateral and longitudinal axes as shown in Figure 12, respectively, using compact servo-based linkages while maintaining a low profile and minimizing structural complexity. Functionally, this morphing mechanism enables the platform to sustain effective six-degree-of-freedom control even under actuator saturation. Compared to other biaxial tiltrotor platforms, QuadPlus demonstrates superior compactness and maneuverability with fewer propellers and a more energy-efficient configuration. The integration of this mechanism with a cascade control architecture including a high-level nonlinear model-predictive control further showcases its robustness in performing complex 3D trajectories with real-time recoverability from saturation events. Overall, the QuadPlus morphing mechanism exemplifies an effective trade-off between actuation richness and structural simplicity, making it a strong candidate for future UAV designs focused on dynamic, contact-based, or cluttered-space operations.

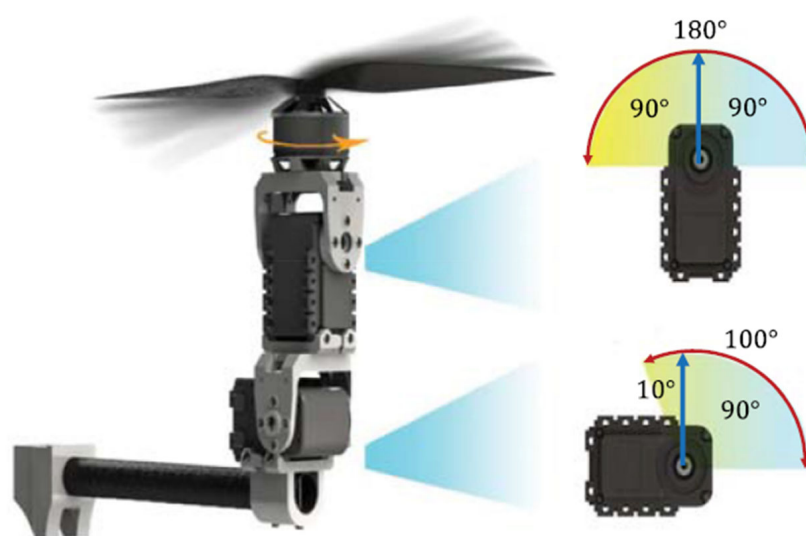


Figure 12. Morphing mechanism of QuadPlus [42].

A novel quadrotor platform was capable of actively adjusting its frame geometry through a morphing mechanism by incorporating four servo-driven rotating arms in addition to the standard four propulsion motors as illustrated in Figure 13; therefore, its system dynamically adapts its morphology in response to payload-induced changes in weight, center of gravity, and inertia tensor [43]. This morphing capability is optimized

through a dual-factor framework that balances energy efficiency and controllability, ensuring stable and efficient flight even under asymmetrical load conditions. Real-time parameter estimation and an adaptive control scheme further enhance the drone's ability to respond to in-flight morphological and dynamic changes. The experimental results, including aerial grasping and dropping tasks, demonstrate superior stability and energy performance compared to conventional fixed-frame quadrotors. This work shows how morphing mechanisms can be integrated into multirotor UAVs to expand their operational flexibility and robustness in payload transport scenarios.

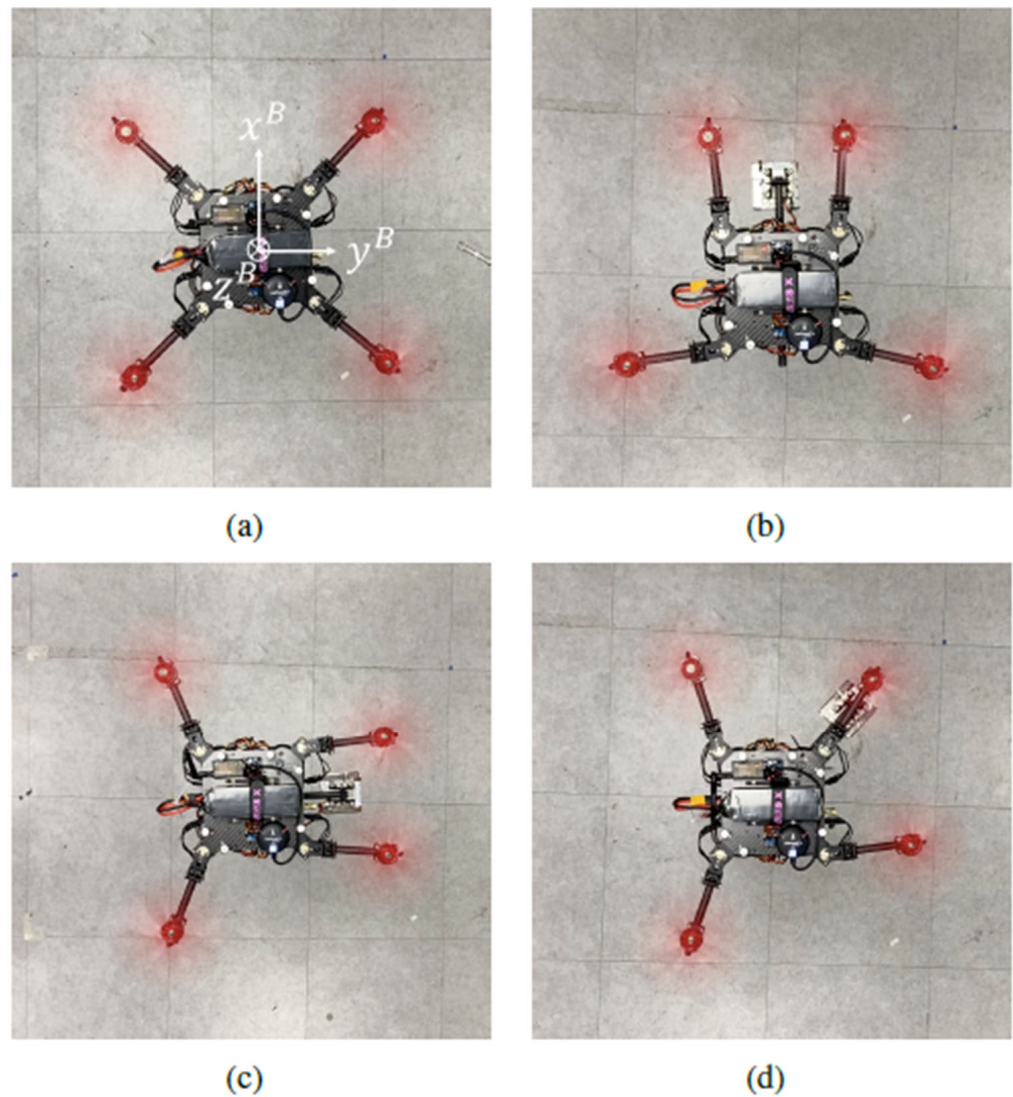


Figure 13. Multiple geometry of a morphing quadrotor: (a) 1 kg payload mounted at $x = 0$ cm, $y = 0$ cm, (b) at $x = +15$ cm, $y = 0$ cm, (c) at $x = 0$ cm, $y = +15$ cm, (d) at $x = 15/\sqrt{2}$ cm, $y = 15/\sqrt{2}$ cm [43].

A bioinspired, actuated folding system enables a quadrotor to dynamically reduce its wingspan by nearly 50% of high-speed navigation through narrow gaps as shown in Figure 14 [44]. Utilizing a lightweight elastic structure driven by a single servomotor, the mechanism allows for rapid folding and unfolding without requiring aggressive maneuvers. This design enhances the drone's agility in cluttered environments while maintaining control authority through a mode-switching strategy and recovery process. The approach demonstrates how morphing can serve as an effective alternative to conventional attitude-based obstacle avoidance in UAV applications.



Figure 14. A bioinspired morphing quadrotor [44].

A dual-actuation strategy significantly enhances the adaptability and fault tolerance of quadrotor UAVs. Each arm of the quadrotor is equipped with a prismatic joint allowing for linear extension and a revolute joint enabling planar rotation about the vehicle's center [45]. This combination of arm extension and rotation shown in Figure 15 facilitates on-demand geometric reconfiguration of the entire rotor layout. Unlike conventional rigid-frame quadrotors, this morphing architecture enables the drone to dynamically shift its mass distribution and rotor positions, allowing for novel hover configurations even under asymmetric thrust conditions, such as rotor failure. By leveraging multibody dynamics and Lagrangian modeling, the authors demonstrate that the vehicle can restabilize itself using only three operational rotors, a capability unattainable in standard designs. This morphing functionality not only enhances robustness but also opens new pathways for control redundancy and mission adaptability in autonomous aerial systems.

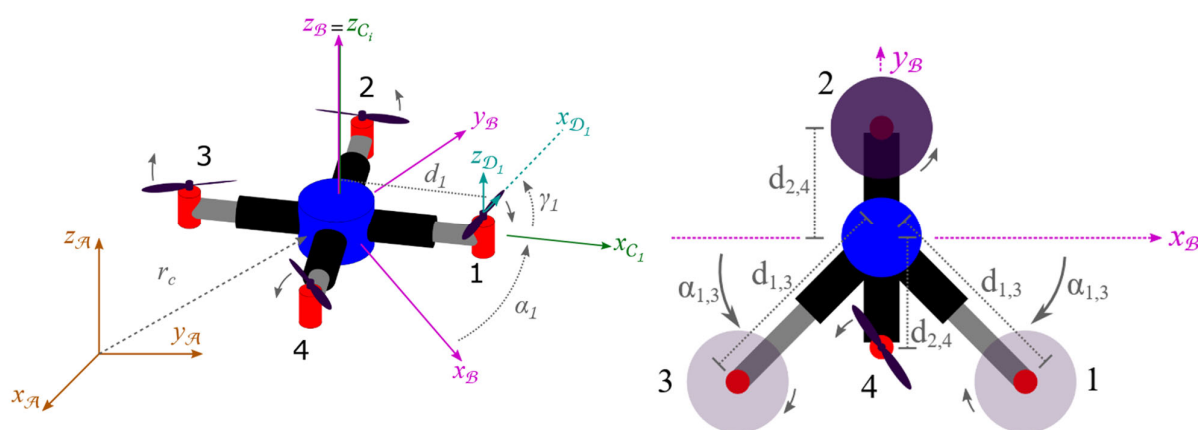


Figure 15. A morphing mechanism for motor failure restabilization [45].

Analytically sophisticated implementation of tensegrity principles was applied to airfoil design. The integration of a shape-controllable tensegrity tail onto a rigid NACA 2412 profile allows the airfoil to dynamically adapt its geometry under various aerodynamic conditions [46]. This integration is achieved through a hybrid structure composed of aluminum bars and rubber string elements, enabling both stiffness and flexibility while maintaining lightweight characteristics. The morphing capability was evaluated using two linearization strategies—model-based and data-driven—offering dual perspectives on

system dynamics: one grounded in physics-based formulations and another in empirical system identification. The simulation results reveal that the morphing airfoil can effectively respond to a variety of excitations, including pulse, step, sine, and white noise inputs, while maintaining structural stability. Notably, the Markov data-based method demonstrates superior alignment under periodic excitations, underscoring its advantage in capturing frequency-dependent behavior, whereas the model-based method shows robustness under broader conditions, particularly in noisy environments. Overall, the mechanism's ability to undergo precise, controlled deformation with minimal error margins highlights its potential for adaptive aerospace applications where real-time aerodynamic optimization is critical.

The tensegrity morphing airfoil offers a lightweight, smooth, and structurally efficient solution for shape adaptation by leveraging pre-stressed rod-cable systems and optimal control strategies [47]. It enables continuous camber changes without discrete flaps, minimizing aerodynamic drag. Compared to traditional morphing methods like Shape Memory Alloy (SMA) wire-actuated flaps, it promises faster response and higher adaptability but faces challenges in fabrication complexity, real-time control, and structural durability. While SMA systems are simpler and already validated with aerodynamic benefits, they are limited by slow actuation and shorter lifespan. Overall, the tensegrity design is a promising next-generation morphing concept, whereas SMA-based mechanisms offer more immediate, though limited, applicability.

The morphing mechanisms can be passively actuated structure that leverages rotary joints and constant-force springs to transition between unfolded and folded configurations [48]. Unlike many morphing drones that rely on active actuators such as servomotors, this design achieves shape change solely by modulating the thrust of the main rotors. The spring-loaded hinges enable each arm to fold downward when the propeller thrust falls below a certain threshold as shown in Figure 16. This bio-inspired folding concept reduces the vehicle's largest dimension by approximately 50%, significantly enhancing its ability to navigate through tight spaces. The morphing process is highly efficient: the mechanism requires no additional weighty actuators, minimizing mechanical complexity and preserving flight dynamics in the default unfolded state. The vehicle design is also well-optimized spring attachment points and force magnitudes were determined through dynamic simulations to minimize configuration transition time while maintaining control authority. Despite some delay observed between theoretical and experimental folding/unfolding times, the mechanical design successfully balances actuation simplicity, responsiveness, and structural robustness during repeated in-flight transformations.

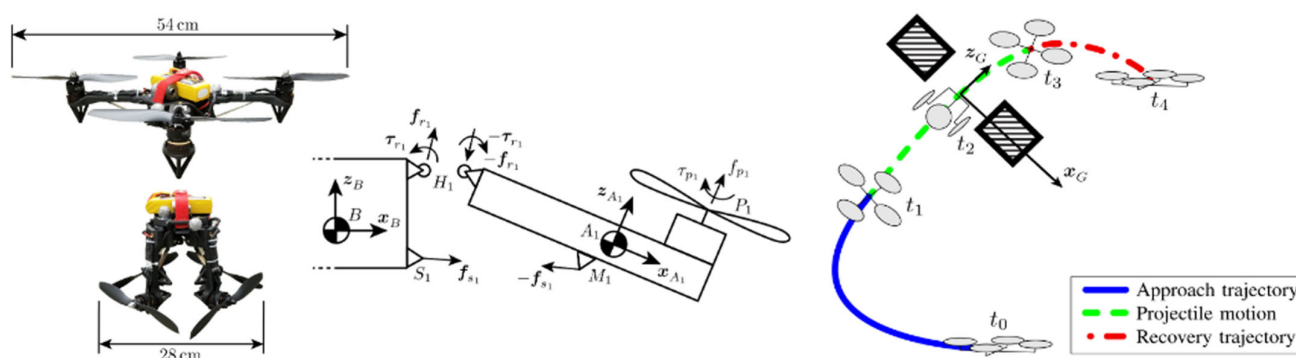


Figure 16. Morphing mechanism of passively actuated structure [48].

The morphing mechanism of the FLIFO drone shown in Figure 17 is a standout feature, offering a fully passive and mechanically elegant solution for size reduction without compromising flight control [49]. By integrating unactuated hinges at each arm and exploiting the reversal of thrust during a controlled flip maneuver, the drone transitions

smoothly between configurations without the need for additional actuators. This design enables a 50% width reduction while maintaining full controllability—an achievement unmatched by comparable morphing UAVs. The mechanism’s geometry is precisely defined through analytically derived hinge angles, ensuring repeatable and symmetric arm folding. Overall, the FLIFO’s morphing system successfully balances structural simplicity, robustness, and functional performance in constrained environments.

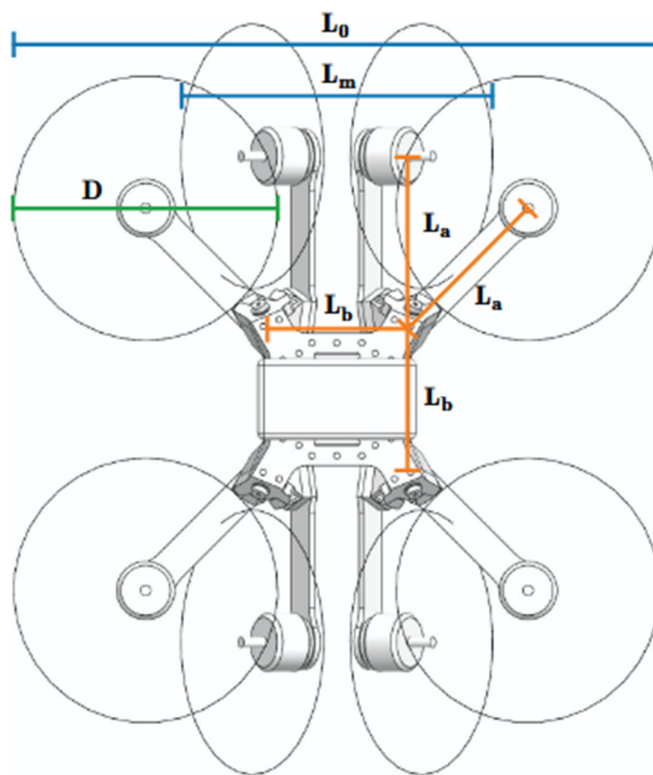


Figure 17. Schematic view of morphing mechanism of FLIFO [49].

The SQUEEZE platform represents a novel class of morphing drones that combine aerial locomotion with physical adaptability for interaction with confined environments. Unlike conventional rigid quadrotors, SQUEEZE, shown in Figure 18, integrates a spring-loaded, reconfigurable frame capable of reducing its diameter through passive compression when encountering obstacles such as narrow gaps or tight spaces [50]. The system leverages a combination of preloaded torsion springs and a central constraint band to maintain structural integrity while allowing deformation. When compressed, the arms are drawn inward, enabling a significant reduction in cross-sectional area—thereby achieving a “squeeze-and-fly” capability. Mechanically, this design avoids complex actuation by using a purely mechanical morphing mechanism, making it lightweight, responsive, and energy-efficient. The control architecture is adapted to account for dynamic changes in the quadrotor’s geometry and center of mass during morphing. Experimental results show that SQUEEZE can stably fly both in expanded and compressed configurations and successfully navigate through gaps smaller than its original span. This approach demonstrates how passive mechanical compliance can be harnessed to enhance situational adaptability in UAVs without relying on electrically powered actuators, providing a promising pathway toward low-complexity, self-morphing aerial robots for inspection, surveillance, and search-and-rescue tasks in constrained environments.

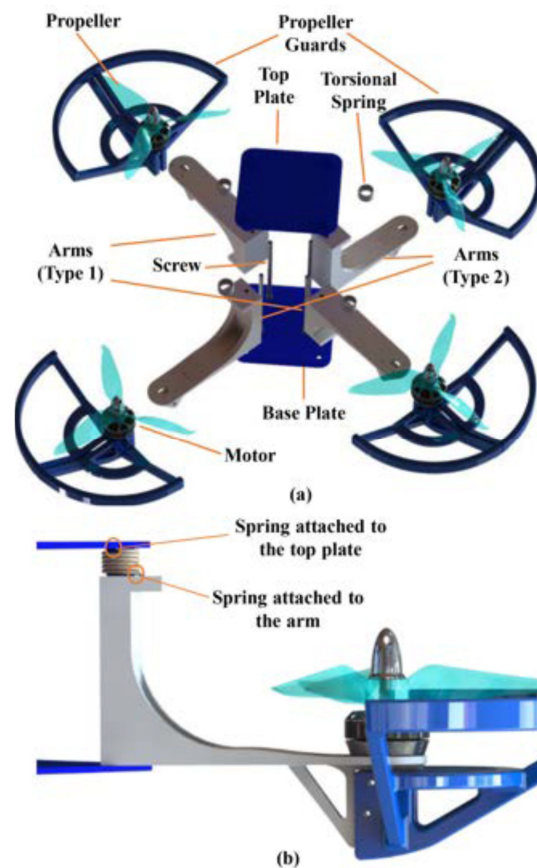


Figure 18. Overview of the SQUEEZE design. (a) Exploded view, (b) Zoomed in view to show how arms are attached to the top plate using the torsional spring, which enables the arms to rotate relative to the top plate when forces are applied on them [50].

The evolving landscape of morphing mechanisms in UAVs and quadrotors have also been focusing on the structural and actuation technologies that enable shape reconfiguration for enhanced flight performance and adaptability. Traditional rigid airframes are being replaced or augmented by reconfigurable architectures capable of span morphing, folding, twisting, and even full-body transformation [51]. Special attention is given to whole-body morphing drones, such as multilink transformable multirotor systems, which extend conventional drone capabilities into areas like aerial manipulation, narrow-space navigation, or multi-modal locomotion as shown in Figure 19.

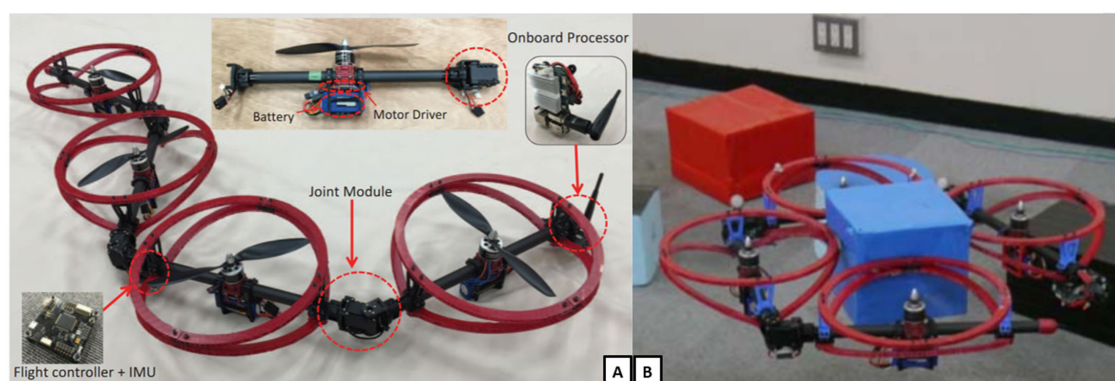


Figure 19. (A): Base structure of proposed multirotor and the link module. At the end of the module, there are joint modules with servo motors, (B): The example of whole-body grasping using the two-dimensional multilink [51].

Various morphing mechanisms have been proposed for UAVs, ranging from compact closed-chain linkages to versatile open-chain designs. Closed-chain systems often achieve rapid and stable reconfiguration with minimal actuators, while open-chain approaches provide greater adaptability through sliding joints, tilting rotors, or compliant structures. Table 1 summarizes these mechanisms, highlighting their actuation methods, morphing capabilities, advantages, and limitations.

Table 1. Mechanisms for morphing.

Platform	Type of Chain (Closed/Open)	Actuation Method	Morphing Capability	Advantages	Limitations	Ref.
Foldable Drone	Open-chain (torsion spring-based passive folding)	Passive torsion springs + elastic constraints	Arms fold inward to reduce diameter for “squeezing” through gaps (%64 size change)	Lightweight, energy-efficient, no active actuators for morphing; enables gap navigation	Limited controllability of morphing process; deformation depends on external forces;	[1]
Skygauge drone	Closed-chain (spherical mechanism)	8 BLDC + 8 servos (total 16 motors)	Full thrust-vectoring; omnidirectional contact/control	Precise force-controlled contact inspection; stable fuselage	High complexity, weight, power draw; limited endurance	[8]
Ring Rotor	Open-chain (string & spring passive retraction + servo)	Single servo + passive springs/strings	Retractable ring; uniform folding (length & width) %56 size change	Lightweight; frees central space for grasping	Limited structural rigidity; modest load capacity	[22]
Sarrus linkage quadrotor	Closed-chain (Sarrus + parallelogram mechanism)	Single actuator (lead screw /servo)	Symmetric linear extension/retraction (~23% size change)	Single-DOF symmetric morphing; stable inertia changes	Limited morphing range; mechanical complexity in linkages	[23]
Biomimetic claw-type design	Closed-chain (parallelogram mechanism 20-link)	Single central servomotor + gear-rack	Eagle-claw inspired vertical folding & grasping, %80 size change	Maintains prop orientation; versatile grasping/perching	Complex multi-link structure; heavier	[24]
FOLLY quadrotor	Closed-chain (four-bar crank-rocker)	Single servo + spur gears	Rapid folding/deploy (0.6 s); ~62.7% volume reduction	Compact, low actuator count; experimentally validated	Mostly pre/post-flight morphing; limited in-flight reconfig.	[33]
MorphoCopter	Closed-chain (4-bar rotary linkage)	Single servo	X → stacked bicopter, ~70% width reduction	Simple actuation; preserves control with tilted props	Only one-dimensional transformation	[34]
X-Morf	Closed-chain (scissor joint + 4-bar)	Servo-driven scissor actuation	Up to ~28.5% span change (0.5 s)	Fast morphing; crash resilience	Dynamic stability challenges; inertia shifts	[35]
M4 (Morphobot)	Open-chain	Multiple motors (4 per arm)	Appendage repurposing: wheels/legs/thrusters (multi-modal)	Exceptional locomotion plasticity; multi-terrain	Heavy, high power & control complexity	[36]
Sliding-arm quadrotor	Open-chain (prismatic sliding joints)	Servo-driven sliding mechanisms	Variable arm length in flight	Inertia/CG adaptation; fault tolerance	Added actuation complexity and mass	[38]
Voliro (tiltable rotors)	Open-chain (tilting rotor arms)	Servo-actuated rotor tilt	Independent rotor tilt for omnidirectional flight	Decouples orientation/position control; wall/contact tasks	Actuation & control complexity; energy cost	[39]
SOPHIE	Open-chain/compliant body	Tendon actuation in TPU structure	Full-body deformation; perching & contact	Lightweight, compliant perching; safe interactions	Requires advanced learning-based control; material durability	[40]
Quadrotor-Blimp	Open-chain (rotating arms + clutch)	Mechanically triggered rotation + elastic strips	Blimp ↔ quadrotor transform (~0.362 s)	Resilient, lightweight transformation; failure response	Limited payload; specialized mission niche	[41]
QuadPlus	Open-chain (biaxial propeller tilting)	Servo-based biaxial linkages	Up to ~100°/180° tilt axes; wide thrust vectoring	High agility; decoupled attitude/position control	Complex control & actuator requirements	[42]
FLIFO	Open-chain (passive hinges triggered by flip)	Passive hinged mechanism (no extra actuators)	50% width reduction via flipping maneuver	No extra actuators; lightweight, simple	Requires a controlled flip maneuver; timing/precision needed	[49]
SQUEEZE	Open-chain (torsion springs, passive compression)	Passive torsion springs + central band	Diameter reduction by passive squeeze, %68 size change	Energy-efficient, gap-navigation capability	Limited active control over configuration	[50]

2.2. Morphing Wings

Morphing wings are a pivotal innovation in UAV design, enabling real-time aerodynamic adaptation across diverse flight regimes through controlled geometric transformation of wing surfaces. Unlike fixed-geometry wings, morphing structures dynamically modify camber, span, sweep, twist, or planform area to meet mission-specific performance requirements such as lift maximization, drag reduction, maneuverability, or loiter endurance. The increasing pressure for sustainable and high-performance aerial systems has brought morphing wings into sharp focus, particularly for next-generation unmanned and hybrid aircraft platforms.

Morphing wings are categorized by their geometric transformation mechanisms such as camber, span, sweep, twist, and folding morphing and their actuation systems, including rigid-link, compliant, and smart material-based mechanisms [52]. Leading implementations range from telescopic wings and variable sweep hinges to continuous-compliant trailing edges.

Projects like SADE (Smart Adaptive Deployable Entry) [53] and SARISTU (Smart Aircraft in a Green Transport System) [54] demonstrated adaptive leading and trailing edges using shape-adaptive ribs and flexible skins, achieving a 3–5% reduction in block fuel consumption through cruise drag reduction and enhanced takeoff lift. These morphing systems replaced conventional flaps and slats with seamless control surfaces, addressing both aerodynamic continuity and structural weight constraints. However, they revealed critical dependencies on compliant skin design, complex actuation kinematics, and aeroelastic stability, particularly under gust loads and dynamic excitation.

Camber morphing, realized through distributed actuation (e.g., finger-rib and belt-rib designs) [55], supports dynamic shape adaptation during takeoff, cruise, and landing. Twist morphing, often enabled by SMAs or elastomer-based compliant structures [56], offers control authority equivalent to ailerons while reducing drag-inducing discontinuities. Span and sweep morphing, especially those demonstrated in telescoping wings and articulated bird-like sweep mechanisms (e.g., RoboSwift [57]), are increasingly utilized in small UAVs for efficiency optimization and maneuverability.

The cellular kirigami morphing wingbox presents a novel approach to achieving morphing capabilities in UAV wings by leveraging foldable honeycomb structures fabricated using kirigami techniques. Unlike traditional origami, kirigami allows both cutting and folding, enabling the creation of complex cellular architectures that can conform to airfoil profiles—specifically the NACA 2415, common in low-speed UAVs [58]. The wingbox is constructed from autoclave-cured Kevlar composite sheets, patterned with precise slits and folds to form a lightweight, partially or fully foldable structure. This configuration enables adaptive camber and trailing edge morphing by integrating artificial hinges formed via selective ungluing during assembly. The resulting structure offers significant torsional stiffness (up to 0.64 Nm^2 with elastomeric skins) while maintaining aerodynamic form and contributing to aeroelastic stability. Additionally, the kirigami method supports multi-position tab deflections without complex actuators, showing promise for integrating compliant materials and embedded piezoelectric actuators. Overall, this morphing wingbox concept provides a scalable, material-efficient, and structurally integrated solution tailored for micro air vehicles and small UAV platforms requiring flight envelope adaptability.

The Zigzag Wingbox is an innovative span morphing concept aimed at Medium-Altitude Long-Endurance UAVs, offering a total 44% span variability ($\pm 22\%$) [59]. Unlike conventional telescopic or folding wing mechanisms, the Zigzag Wingbox features a partitioned morphing section composed of rigid spars and ribs joined by bevel-hinged beams, allowing controlled structural articulation. The root section remains rigid to carry primary loads and house fuel, while the morphing section provides adaptability through modular, zigzag-configured partitions. A flexible skin is used to maintain aerodynamic smoothness during morphing. The study emphasizes the importance of mechanical simplicity, load-path continuity, and mass-efficiency, noting that the design avoids excessive penalties on stiffness and weight. Preliminary aero-structural sizing and modeling validate the structural feasibility of the concept under various flight conditions. The paper also highlights trade-offs, particularly the increase in aeroelastic deformation with extended span, underscoring the need for a balance between aerodynamic benefit and structural integrity. Overall, the Zigzag Wingbox demonstrates a mechanically viable and structurally effi-

cient approach for in-flight span adaptation, supporting mission flexibility and enhanced aerodynamic performance in long-endurance UAVs.

The GNATSpar (Gear driven Autonomous Twin Spar) [60] is a morphing wing concept as a practical solution for UAV span extension. Unlike traditional telescopic designs, GNATSpar uses a pair of opposing spars housed within the fuselage and driven by a rack-and-pinion system with self-locking worm gears, allowing symmetric span variation up to 20%. The wing is covered by a flexible latex skin and uses sliding ribs to preserve aerodynamic continuity throughout the morphing cycle. Structural analysis and finite element modeling confirmed sufficient strength under flight loads, while wind tunnel tests demonstrated improved lift-to-drag ratio with extended span. However, span extension also led to increased aeroelastic deflection, highlighting a design trade-off between aerodynamic benefit and structural stiffness. The GNATSpar concept exemplifies a mechanically efficient, low-weight, and field-deployable span morphing solution for small UAVs.

Clean Sky 2 [61] is a flagship EU research initiative aimed at greening aviation. This program included in-flight testing of morphing winglets and adaptive wingtips on regional aircraft. While successful in validating large-scale morphing under operational conditions, it exposed integration hurdles related to load transmission between morphing elements and rigid structures. Scalability and mass penalties for embedded actuation and compliant skin systems remain key bottlenecks.

SABRE (Shape Adaptive Blades for Rotorcraft Efficiency) [62] was a H2020 project focused on blade-level morphing for helicopters. Although rotorcraft present unique challenges (cyclic loading, high RPM), the SABRE project demonstrated the feasibility of embedded morphing mechanisms. However, durability under fatigue and fault-tolerant control of actuation systems remains unresolved, particularly under high-vibration regimes.

SARISTU [54] was a major FP7 project. SARISTU achieved significant milestones in trailing edge morphing and integrated sensor-actuator systems as shown in Figure 20. However, full-scale testing revealed cross-coupling effects where deformation in one morphing segment (e.g., droop nose) unintentionally affected adjacent subsystems (e.g., winglet flaps), underscoring the need for more advanced decoupled control strategies and predictive aeroelastic modeling.

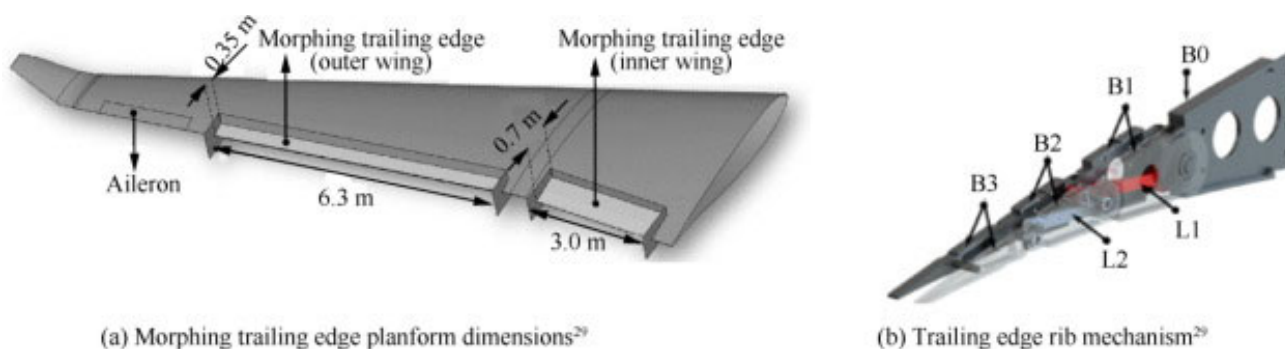


Figure 20. Morphing trailing edge planform dimensions and trailing edge rib mechanism [63].

SADE [53] focused on laminar flow preservation through adaptive leading edges as shown in Figure 21, SADE highlighted that droop nose morphing could yield a 10% lift improvement during takeoff. Yet, integration with deicing systems, bird-strike protection, and maintenance accessibility posed substantial design constraints.

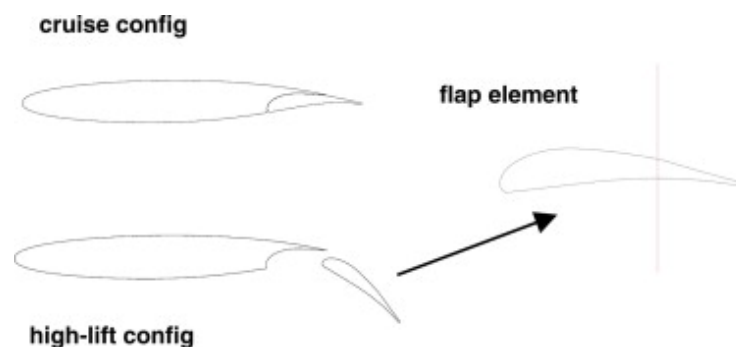


Figure 21. Illustration of single-slotted flap applied on wing airfoil [64].

The morphing mechanism of the UAS-S4 combines telescopic wingspan and variable sweep, offering aerodynamic flexibility as shown in Figure 22 [65,66]. While this concept is promising, the paper emphasizes control design, particularly fuzzy and Lyapunov-based adaptation without detailing the mechanical structure, actuation limits, or real-world morphing performance. The lack of experimental validation and structural analysis limits the practical evaluation of the morphing system, despite its theoretical control robustness.

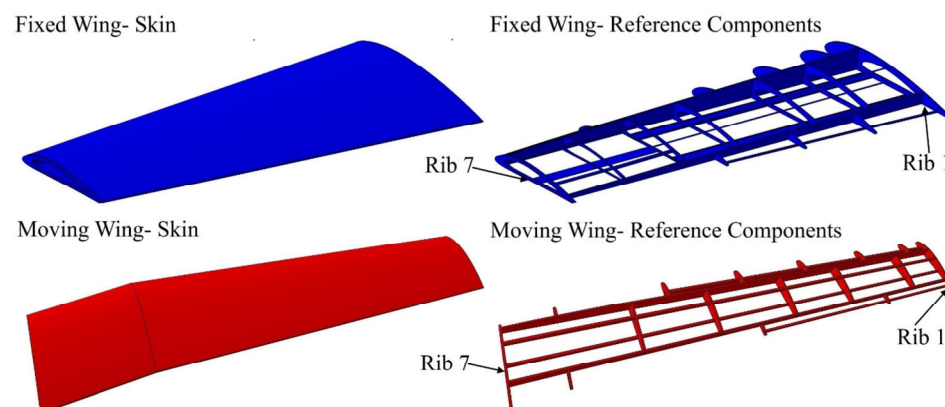


Figure 22. Geometrical model configuration of fixed and moving segments with their components, according to topology optimization [65].

MDO-505 and GARDN [67] is the Canada-Italy collaboration focused on wind tunnel validation of an adaptive aileron integrated within a morphing wing segment as shown in Figure 23. While it demonstrated actuation feasibility and flow control in a lab environment, transition to flight-scale readiness was limited by actuator bandwidth, stiffness limitations, and unmodeled structural hysteresis. The aerodynamic optimization of a morphing wing-tip demonstrator showcases a mature integration of morphing technology with computational optimization. Through the use of an ‘in-house’ genetic algorithm (GA), alongside artificial bee colony and gradient descent methods, to delay or advance boundary layer transition, the upper surface morphing of two airfoil types was optimized, aiming at drag reduction or flow stabilization. The experimental validation within wind tunnel campaigns and using actuator-driven composite skins was conducted [68]. The morphing surface, driven by actuators placed within a realistic wing-box structure, demonstrates adaptable deformation aligned with aerodynamic targets, achieving transition improvements of up to 31.85% of the chord. The methodology is rooted in a multidisciplinary design approach, combining aerodynamics, structural constraints, and control integration. However, while the genetic algorithm’s effectiveness is robustly demonstrated, the paper emphasizes algorithmic behavior more than the structural implications of morphing (e.g., fatigue, response time), which are critical for real-world deployability.

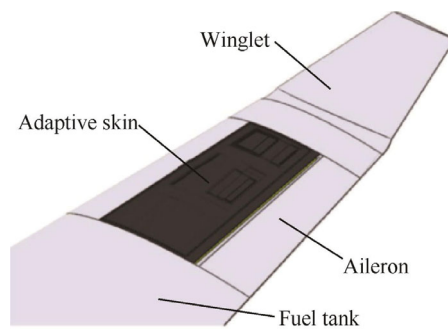


Figure 23. The layout of the morphing skin on the aircraft wing [67,68].

The Optimized Aerofoil Method (OAM) reshaped the UAS-S45 aerofoil for improved dynamic stall performance, achieving enhancements in lift, delayed flow separation, and reduced hysteresis through aerodynamic optimization [69,70]. While the methodology itself is purely numerical and static, its implications are highly relevant to the design of morphing airfoil mechanisms. Specifically, the optimized profiles suggest that small but well-targeted shape changes, especially at the leading edge and suction surface as shown in Figure 24 can deliver measurable gains in unsteady flight conditions typical for UAVs.

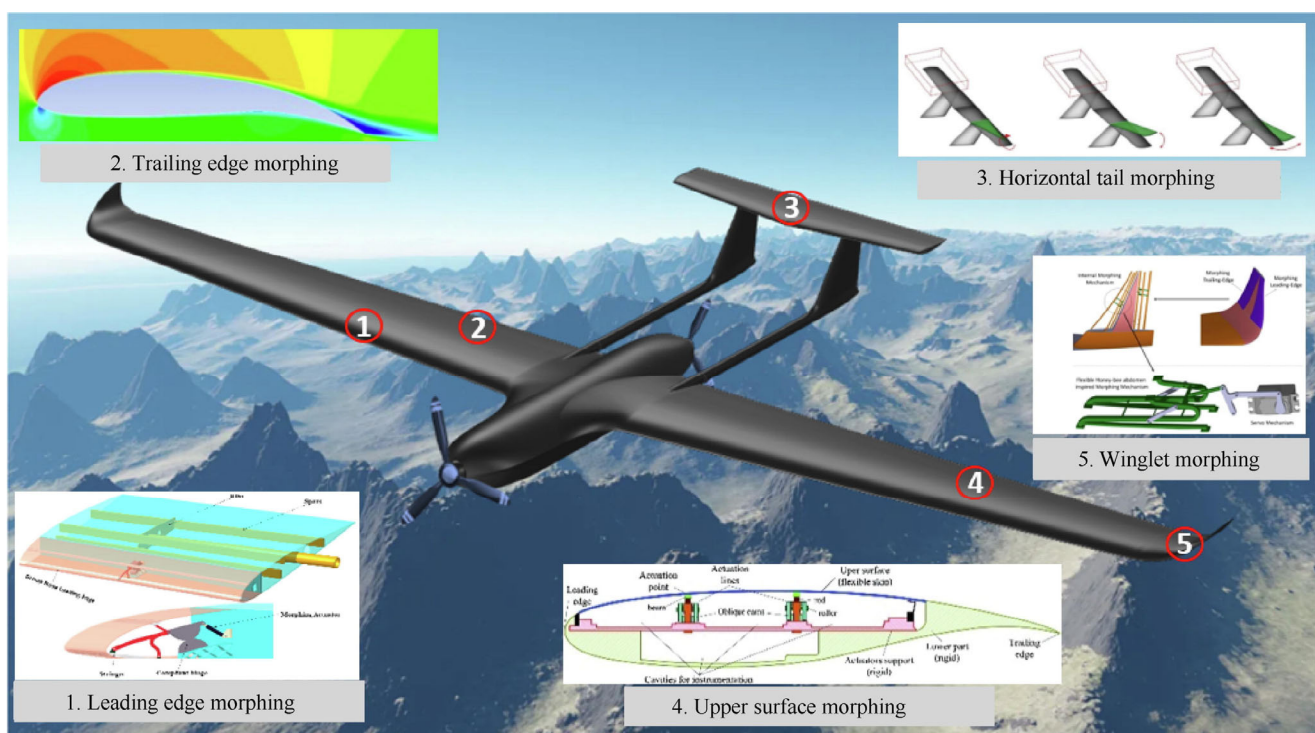


Figure 24. Morphing studies on UAS-S45 conducted at LARCSE [69].

CLEEN (Continuous Lower Energy, Emissions, and Noise) [71] is sponsored by the Federal Aviation Administration and International Civil Aviation Organization. CLEEN targeted system-level emission reductions. Morphing wings formed part of its broader sustainability vision. Though several subsystem-level demonstrations were achieved, morphing-specific maturity was deemed insufficient for near-term commercial integration without further development in materials, controls, and certification protocols.

CASCADE (Complex Adaptive System Composition and Design Environment) [72] is a program backed by the Defense Advanced Research Projects Agency and emphasized modeling and simulation environments for adaptive systems. It advanced the virtual design

infrastructure needed for morphing components but lacked physical demonstrators. The tools it developed now underpin many simulation-based design loops for morphing UAVs.

ACTE (Adaptive Compliant Trailing Edge) [73] is one of the earliest large-scale morphing flight tests. ACTE demonstrated compliant trailing edge morphing on a Gulfstream GIII business jet via continuous flexible skins developed by FlexSys as shown in Figure 25. Though showing 2–11% fuel savings, issues such as aeroelastic instability, nonlinear stiffness, and manufacturing cost hindered broader adoption. Moreover, the increased degrees of freedom led to control complexity and necessitated high-fidelity modeling for safe operations.

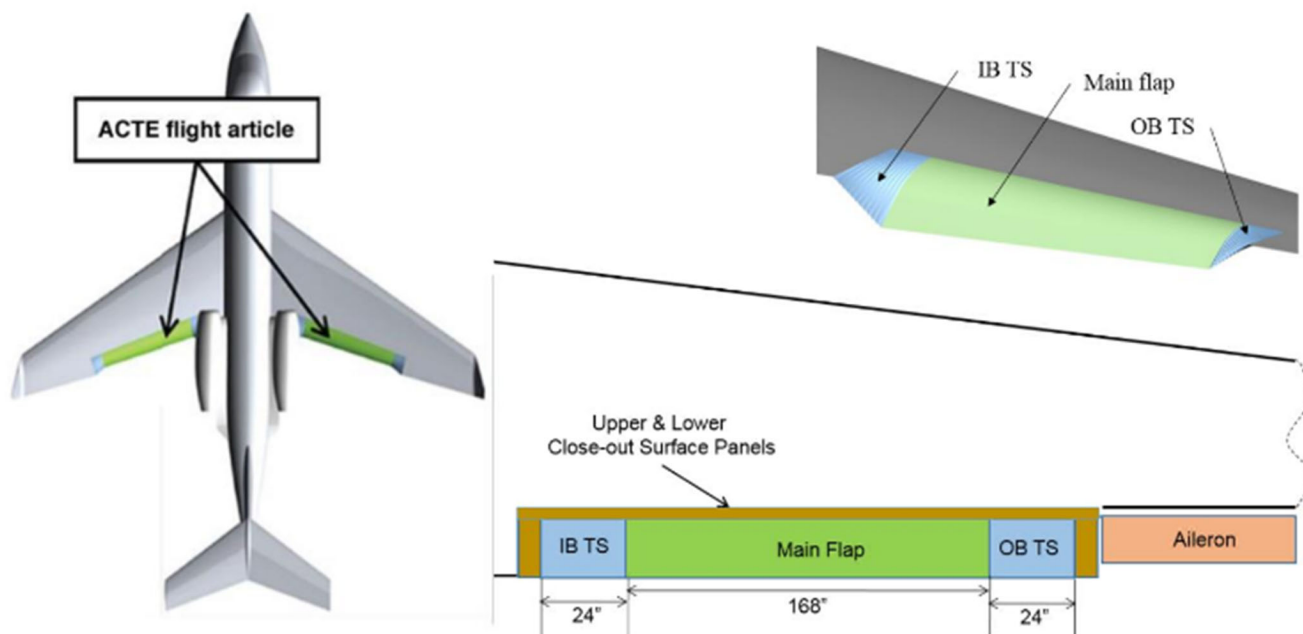


Figure 25. ACTE flap components as installed for flight-testing [73].

Despite the substantial progress achieved, all these programs collectively reveal systemic challenges: (1) high actuation energy demand relative to UAV size constraints, (2) insufficient durability of compliant structures under cyclic loading, (3) complexities in structural integration without mass penalties, and (4) aeroelastic instabilities due to increased degrees of freedom and continuous deformations.

Current morphing designs often suffer from the “flexibility–rigidity paradox”—the structural skin must accommodate large deformations without compromising stiffness or airworthiness [74]. Advances in zero-Poisson-ratio skins, layered hybrid composites, and topology-optimized lattice structures are beginning to address this, enabling smooth deformations with embedded strength.

Control complexity also scales with morphing degrees of freedom. This has catalyzed research in model predictive control (MPC), reinforcement learning, and adaptive inverse kinematics tailored to morphing structures [75]. Real-time feedback from integrated fiber optic sensors and strain gauges will be central in enabling autonomous morphing behavior under uncertain flight conditions.

A study for its validation through both hardware-in-the-loop (HIL) simulations and real-world flight tests, demonstrates that morphing operations can be autonomously executed without sacrificing stability or control performance [76]. However, the control strategy relies on pre-programmed logic and fixed gain scheduling, lacking adaptability to unanticipated conditions. The absence of intelligent control methods such as adaptive algorithms, fuzzy inference, or reinforcement learning limits the UAV’s responsiveness in

dynamic environments. Additionally, while the aerodynamic implications of morphing are well considered, the study does not sufficiently address the structural or mechanical trade-offs such as mass penalties, actuation reliability, or fatigue.

Table 2 summarizes major projects on morphing wing strategies, ranging from large-scale programs like SADE, SARISTU, and ACTE to UAV-focused concepts such as the Zigzag Wingbox and GNATSpar. These efforts demonstrate the aerodynamic benefits of morphing, while also exposing key challenges in aeroelastic stability, actuation complexity, and structural durability.

Table 2. Critical projects on morphing strategy for wings and outcomes.

Project Name	Morphing Strategy	Scale	Key Outcomes	Ref.
SADE	Adaptive trailing edge with finger-rib mechanism	Full-scale (A320 model)	Demonstrated ~3% drag reduction in cruise, improved lift in takeoff	[53]
SARISTU	Morphing droop nose, trailing edge, winglet	Full-scale (A320 outer wing section)	Validated multi-functional skin and actuator integration	[54]
ACTE	Seamless trailing edge deformation (compliant mechanism)	Full-scale (GIII testbed)	Successful flight tests with noise and drag reduction	[73]
RoboSwift	Variable sweep via feather-like wings	Small UAV (bird-scale)	Improved maneuverability and stealth through bio-inspired sweep actuation	[57]
GNATSpar	Spanwise extension via telescoping spars	Wind tunnel scale	Demonstrated up to 40% span increase, maintaining structural stiffness	[60]
Zigzag Wing Box	Span morphing with zigzag box geometry	Subscale	Achieved adaptive span with reduced bending stiffness impact	[59]
SARISTU	Flexible composite morphing leading edge	A320 model	Maintained laminar flow; ~10% lift improvement at high AoA	[54]
Wingbox	Combined twist and sweep via smart actuators	Small UAV	Validated twist morphing with distributed sensors and control	[58]
Clean Sky 2	Double-flapped active winglet	Transport scale	Gust load alleviation and improved fuel efficiency (~3% reduction)	[61]
MDO-505	Combined variable camber and twist morphing	Wind tunnel scale	Demonstrated multi-objective MDO techniques; validated shape-adaptable structures in subscale tests	[67]
UAS-S4	Telescopic wingspan and variable sweep	Simulation-Based Testing	Morphing surface of the airfoil between 20% and 65% of the chord	[66]
UAS-S45	Deflection of the wing tip around a hinged axis.	Wind tunnel scale	delayed the laminar-to-turbulent transition, especially in the 0.15–0.25 Mach range and angle of attack between -3° to $+3^\circ$.	[77]
Navion L-17	Variable wingspans and sweep angles	Numerical simulation	the lift-drag ratio can be effectively improved by 1–2.	[76]

2.3. Control

Effective control of morphing quadrotors is critical due to the dynamic variations in inertia, center of gravity, and aerodynamic properties introduced by in-flight reconfiguration. Unlike fixed-geometry UAVs, these platforms require advanced control strategies to ensure stability and precise trajectory tracking. Moreover, dynamic characters of morphing UAVs can be changed based on the conditions of application.

The control system of the UAS-S45 employs a hybrid approach combining LQR, PI-FF, and Generalized Extended State Observers to manage flight stability and trajectory tracking across varying conditions. To address system nonlinearities, a gain scheduling method using ANFIS-Fluent interpolation is implemented [25], enabling adaptive tuning of control gains throughout the flight envelope. Validated against MIL-STD-1797A standards [78], the system achieved high stability performance with over 90% success in lateral dynamics.

Dynamically, Skygauge drone introduces nontrivial coupling between attitude control and force application, requiring coordinated rotor modulation and feedback-driven stabilization strategies to maintain performance under varying contact conditions [8]. However, the design's inherent symmetry and real-time control architecture ensure robust equilibrium even during force-on-surface interaction. This capacity is crucial for executing ultrasonic thickness measurements, where consistent contact pressure and positional repeatability are paramount. By eliminating the need for external bracing, scaffolding, or rope access, the Skygauge system achieves a significant increase in operational efficiency—exceeding manual inspection speeds by an order of magnitude—while also mitigating occupational hazards. In sum, the Skygauge drone exemplifies a highly integrated morphing UAV platform, where mechanical articulation and control dynamics are optimized due to the morphing mechanism.

A robust framework for the dynamics and control of morphing quadrotors is developed by integrating nonlinear modeling, PID control, morphing mechanics, and battery optimization. Dynamics is modeled using the Newton–Euler method, with real-time updates to inertia based on morphing arm lengths [79]. A Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm optimizes PID gains, morphing ratio, and battery weight, while an Artificial Neural Network estimates energy density. The system effectively adapts to changes in geometry and mass, maintaining trajectory tracking and improving endurance. The optimization led to a 27.2% cost reduction and increased flight time from 35.2 to 39.3 min, demonstrating a highly effective control-performance synergy in morphing UAVs.

An advanced control framework for morphing quadrotors operating in restricted environments lies in a nonlinear cascaded controller that dynamically adjusts to real-time changes in inertia, center of gravity, and aerodynamic drag caused by morphing [80]. Unlike traditional PID or LQR-based methods, this controller does not rely on small-angle assumptions and uses differential flatness for accurate trajectory tracking. An online thrust coefficient estimator based on recursive least squares ensures consistent thrust performance despite propeller overlap during deformation. Additionally, a dedicated servo control loop manages arm rotations based on deformation commands. The control system is validated through simulations and real-world experiments, showing superior stability, responsiveness, and accuracy in narrow and dynamic environments compared to conventional controllers.

A data-driven control approach was employed for tensegrity-based morphing airfoils. By leveraging Markov data, it achieves precise shape tracking without relying on detailed dynamic models [81]. This approach enhances robustness to modeling errors and eases controller design. However, its performance is sensitive to data quality and coverage, and scaling to complex morphing systems may demand extensive data collection. Overall, it's a promising, model-free direction that complements traditional physics-based control methods.

A two-layer control system is designed: a PID-based position controller and a PD-based attitude controller that accounts for changes in the moment of inertia [82]. The morphing mechanism alters the quadrotor's size without changing its mass, which affects its agility and stability. The controller handles these variations effectively by integrating

inertia functions based on the morphing angle. Both simulations and experiments show that the quad-rotor can maintain accurate path tracking and stable hovering without needing to re-tune control gains even under disturbances such as winds. Overall, the study demonstrates that a unified control framework can successfully manage dynamic morphology in flight.

Traditional methods often isolate flight and morphing control or treat morphing as an external disturbance. In contrast, coordinated control architecture synchronizes both aspects via a dual-controller scheme: (1) a morphing-specific Multi-Expert Weighted Combination-based Flight Controller (MEWC-FC) and a flight-state-dependent morphing controller [83]. Notably, the MEWC-FC leverages Extreme Learning Machine and (2) Particle Swarm Optimization (ELM-PSO) for expert selection and combination weight initialization, and it is later fine-tuned using reinforcement learning based on Proximal Policy Optimization. This control formulation supports zero-shot generalization to unseen morphologies, demonstrating robustness and adaptability without requiring morphology-specific retraining. Furthermore, the flight controller outputs are morphing-aware, and the morphing actions are informed by current flight states, creating a truly bidirectional control loop. The simulation results validate this design, showing enhanced trajectory tracking, improved reward accumulation, and superior performance even under actuator noise. This integrated RL-based control architecture represents a significant step toward intelligent, adaptable UAVs capable of exploiting their morphing capabilities for dynamic mission profiles.

The passive morphing feature is integrated into conventional quadrotor flight dynamics. In the unfolded state, the drone retains the standard 6-DOF control framework, using a position controller to adjust the thrust direction and a cascaded attitude controller for torque generation [48]. This control scheme concerns in its adaptation to the mechanical constraints imposed by the morphing mechanism—specifically, ensuring that the thrust forces are sufficient to counteract the spring torques that drive arm folding. To prevent unintended morphing during aggressive maneuvers, control inputs are bounded using a derived from inequality involving the total thrust and body torques. These constraints are elegantly converted into a saturation strategy that hierarchically prioritizes yaw, then total thrust, and finally roll/pitch adjustments. Moreover, the folding and unfolding transitions are initiated deliberately by commanding increase or reduction in thrust, and the controller automatically resumes standard behavior once the desired configuration is reached. The authors demonstrate the effectiveness of the control method through gap-traversing trajectories that coordinate both trajectory planning and configuration shifts. While the added control constraints reduce yaw authority and impose a minimum thrust, the overall strategy ensures robust and predictable flight behavior during morphing.

Handling time-varying dynamics, model uncertainties, and external disturbances are critical issues of control systems of morphing quadrotors [84]. A segmented modeling approach was developed to allow the system to explicitly account for changes in the UAV's mass distribution and inertia during morphing operations. This segmentation simplifies the analysis and control of the complex nonlinear and time-varying behavior introduced by structural transformation. The control architecture is built upon a constraint-following strategy, translating trajectory and posture tracking tasks into state and input constraints. This architecture provides an inherent safety mechanism, ensuring that the UAV operates within predefined performance bounds. The proposed controller does not require precise knowledge of delay bounds or external disturbances, making it robust to real-world operating conditions, such as winds or actuator lags. Lyapunov stability theory is used to prove uniform ultimate boundedness of the tracking error, ensuring that the UAV stays close to its desired trajectory despite uncertainties. Simulations under morphing

conditions including inertia changes, control delays, and disturbances show improved robustness over conventional methods.

A morphing quadrotor can maintain stable flight using a standard off-the-shelf Pixhawk controller with an unmodified PID-based firmware (ArduPilot v3.4.1), even as its geometry passively changes in flight [85]. Over 350 test flights across different morphing configurations and trajectories were conducted, showing that despite reductions in pitch and roll damping—up to 65% in the most morphing cases—the quadrotor remained controllable and stable without requiring any controller retuning. Notably, yaw dynamics was unaffected, and trajectory tracking improved at higher speeds and waypoint densities, highlighting a degree of robustness in the default control system. From a control perspective, this study offers strong evidence that conventional PID controllers possess sufficient tolerance to handle moderate morphing without specialized adaptation. However, the observed reduction in dynamic responsiveness, especially in pitch and roll, signals performance limits under more aggressive maneuvers or larger geometric variations. This work thus establishes a valuable baseline and suggests that incorporating adaptive or model-based control could further enhance model performance while retaining the practical benefits of passive morphing designs.

Tackling the complex control challenges of over-actuated morphing UAVs differs significantly from conventional drones due to their changing morphology, asymmetry, and nonlinear dynamics [86]. The proposed system divides control into its two main subsystem parameters: attitude and position. For attitude stabilization, an Adaptive Nonsingular Fast Terminal Sliding Mode Controller (ANFTSMC) is used, while an Integral Backstepping Controller (IBC) handles position control, both grounded in Lyapunov theory. To optimize control gains, the Whale Optimization Algorithm (WOA) is employed. The effectiveness and robustness of the proposed control strategy are validated through a comparative study with conventional methods.

The Model Predictive Control (MPC) and the end-to-end Reinforcement Learning (RL) for executing the complex quadrotor morpho-transition maneuvers are compared. From a control standpoint, the RL-based approach demonstrates superior adaptability and robustness by directly mapping state observations to motor commands, successfully handling high tilt landings, observation delays, and even partial actuator failures without explicit modeling [87]. It outperforms the MPC in disturbance rejection up to a certain threshold and achieves smoother, lower-impact landings. However, the RL shows minor instabilities due to system latency. In contrast, the MPC method, while more stable in angular dynamics and easier to implement without hardware-specific tuning, lacks robustness to unmodeled dynamics and actuator degradation. Overall, the study highlights the RL's potential for agile and fault-tolerant control in dynamic, contact-rich environments where conventional model-based methods face limitations.

A control strategy for a continuously morphing quadrotor of which arm lengths can vary in-flight, significantly affecting the system's moment of inertia and dynamics is a critical issue of the literature. To address these time-varying and nonlinear effects, the Sliding Mode Control (SMC) approach is employed, with the controller gains optimally tuned via Particle Swarm Optimization (PSO) [88]. This combination enables the system to maintain stability and precise trajectory tracking even during morphing maneuvers. Simulation results across simple and complex 3D paths show that the PSO-optimized SMC significantly outperforms a baseline PID controller, achieving up to 35% lower RMSE, 40% faster settling time, and reduced control chattering. The control algorithm dynamically compensates for transient torque demands that occur during rapid inertia shifts, maintaining control continuity and responsiveness. However, the study's limitations include the lack of experimental validation, assumptions of symmetric arm morphing, and ab-

sence of formal stability proofs such as Lyapunov-based analysis. Despite these gaps, the work offers a promising control framework for variable-geometry UAVs, demonstrating that intelligent tuning of nonlinear robust controllers can yield high-performance and fault-tolerant behavior in morphing aerial platforms.

The FLIFO drone represents a novel advancement in UAV control systems through its integration of passive morphing with dynamic, configuration-aware control logic [49]. Unlike conventional morphing drones that require additional actuators and often are affected from control loss during shape transitions, the FLIFO maintains full flight controllability across both its un-morphed and morphed states by relying solely on flight actuators, and by a precisely designed hinge mechanism triggered by an intentional inversion maneuver. The control system, built using a modified PX4 autopilot running on a Pixracer R15, incorporates a custom feedforward-based transition controller that governs the flipping motion required for morphing without real-time feedback, emphasizing simplicity and reliability. Crucially, the system switches between pre-defined actuator effectiveness matrices (E) and thrust coefficients (CT) to account for the altered aerodynamics and thrust vectoring in each configuration. Experimental data reveal that while upward thrust and roll torque effectiveness drop significantly in the morphed state (by 48% and 70%, respectively), yaw control improves dramatically, indicating a need for careful weight distribution and potential future optimization. The adaptive control adjustments effectively compensate for the asymmetric performance characteristics between the two configurations, allowing the drone to consistently and robustly perform morphing maneuvers, as demonstrated in 112 consecutive successful transitions. This approach not only proves the feasibility of passive morphing with retained control authority but also showcases a lightweight yet functionally sophisticated control strategy that bridges mechanical simplicity with advanced performance adaptability in morphing UAVs.

QuadRotary, a dual-mode aerial robotic platform integrates the agility of a quadrotor with the hovering efficiency and panoramic perception capabilities of a rotary-wing vehicle through an in-flight reconfigurable architecture [89]. This platform has an innovative use of passive mechanical components—namely, magnet-assisted hinges and self-foldable airfoils—allowing bidirectional transitions between the two flight modes without additional actuators. From a control perspective, the authors develop a unified modeling and control framework that accommodates the fundamentally different dynamics of both configurations. By employing a Lyapunov-based attitude controller and a cascaded position controller, the system ensures stable flight in both modes, with smooth and rapid transitions managed solely through motor thrust modulation. Particularly notable is the departure from conventional Euler angle control in rotary-wing mode, where the system instead stabilizes the body z-axis and yaw rate due to the continuously spinning frame. This design choice allows for high yaw-rate hovering, expanding the platform's potential for applications requiring omnidirectional sensing or rapid repositioning. Actuator input allocation is managed via tailored control matrices for each mode, ensuring effective thrust and torque distribution under varying structural geometries. Experimental validation in a motion capture environment confirms the robustness and agility of the control system, with position errors below 0.15 m and yaw rate tracking errors under 0.7 rad/s. Additionally, power consumption analysis reveals an 18.4% gain in efficiency during rotary-wing hovering, highlighting the practical benefits of the design. Overall, the study demonstrates a thoughtfully integrated solution where mechanical design and control algorithms are co-optimized, resulting in a versatile, efficient, and mechanically simple UAV platform suitable for diverse aerial tasks.

HEXmorph presents a robust nonlinear geometric tracking controller for morphing quadrotors capable of transitioning between multiple configurations (H, T, X, Y) [90]. The controller operates directly on a manifold called $SE(3)$, enabling unified position and at-

titude tracking without switching control laws for different morphologies. It effectively handles time-varying inertial properties and shifts in the center of gravity caused by structural transformation. Unlike optimization-based or adaptive control methods, the Nonlinear Geometric Tracking Controller provides analytically guaranteed global exponential stability through Lyapunov-based analysis. Real-time flight experiments validate its robustness and precise tracking performance during in-flight morphing, making it a reliable and mathematically rigorous solution for control of over-actuated, reconfigurable UAVs.

A conventional cascaded PID control system to manage flight across varying configurations is enabled by servo-actuated arm adjustments. The control architecture consists of an inner-loop attitude controller and an outer-loop position controller, with fixed gains tuned through empirical testing [91]. Rather than introducing advanced or adaptive strategies, the study focuses on assessing how traditional control responds to dynamic changes in system inertia and geometry during morphing. Results show that while the PID controller can maintain flight stability within a defined envelope, morphing significantly affects control responsiveness and performance. The limitations of fixed-gain controllers during rapid configuration changes are highlighted.

A New Overactuated Multirotor Prototype: Quad3DV has a comprehensive approach to the modeling and control of an overactuated UAV platform with tilting rotors. From a control and modeling standpoint, the study constructs a full 6-DOF dynamic model using Newton–Euler equation, capturing the complex coupling effects between the UAV’s translational and rotational dynamics. A notable aspect of the modeling is the use of quaternion-based attitude representation [92], which ensures singularity-free tracking of the vehicle’s orientation and enables smooth handling of large-angle maneuvers. This quaternion framework is particularly suitable for the control of overactuated systems, where fine-tuned coordination between multiple actuators is required. The control strategy employs feedback linearization, allowing decoupling of the nonlinear system dynamics and enabling precise tracking of reference trajectories in both position and orientation. Moreover, an actuator allocation scheme is developed to distribute control efforts across redundant tilting rotors, enhancing the system’s ability to handle external disturbances and perform aggressive maneuvers. Simulation results confirm the controller’s robustness and the advantages of overactuation in expanding the UAV’s control authority. Overall, the paper offers a solid integration of advanced modeling, quaternion-based attitude control, and overactuated control allocation, making it a strong contribution to the field of UAV control.

Particularly under the influence of Dryden wind gust disturbances, the dynamic behavior of a quadrotor UAV equipped with a vertically oscillating payload was developed [93]. By modeling the UAV–payload system with a flexible attachment, the authors highlight the complex vibration and trajectory control challenges during three distinct flight phases—takeoff, cruise, and landing. Two controllers, Proportional Derivative (PD) and Sliding Mode Control (SMC), are developed and compared based on trajectory tracking and vibration suppression performance. Through simulation, it is demonstrated that the SMC controller outperforms the PD, especially under external gust disturbances, with up to 88.6% reduction in vibration energy (P2 phase). The study further utilizes Fast Fourier Transform (FFT) and integral performance indices (IAE, ITAE) to quantify the oscillation characteristics. While the paper offers meaningful contributions in modeling and control evaluation, it could benefit from experimental validation to confirm the real-world applicability of the proposed methods, and an analysis of controller robustness under varied payload masses and attachment stiffnesses.

A novel vibration suppression system for quadrotor UAVs using Shape Memory Alloy (SMA) springs integrated into the payload suspension mechanism was improved. The system aims to reduce structural vibrations transmitted from the UAV body to the payload

during flight [94]. A dynamic model of the UAV–payload system and the damping effects of SMA springs using both numerical simulation and experimental validation was analyzed. Results show that SMA springs significantly decrease vibration amplitude, particularly under dynamic payload motions. While the study effectively demonstrates the feasibility of SMA-based damping, it is limited by a lack of detailed sensitivity analysis regarding the SMA material properties and operational conditions (e.g., temperature variations and fatigue behavior). Furthermore, real-time adaptability and long-term reliability of the SMA mechanism under varying flight scenarios remain unexplored. Despite these limitations, the paper contributes a promising passive vibration control technique that complements existing active control strategies in UAV-based transport and inspection missions.

The structural flexibility in quadrotor UAVs influences the dynamics of tethered payloads during various flight maneuvers. By modeling both rigid and flexible UAVs, provide comparative insights into system behavior under translational and rotational movements. The study uses a coupled multibody simulation framework incorporating cable dynamics and UAV flexibility, revealing that even modest structural compliance in the UAV can significantly alter payload swing amplitude and control performance [95]. While the inclusion of flexibility yields a more realistic representation of actual UAV behavior, the study primarily focuses on simulation and lacks experimental validation. Furthermore, the impact of active control strategies to mitigate these oscillations in flexible configurations is not explored, leaving a gap in practical application. Nonetheless, the work contributes valuable theoretical insights that highlight the importance of considering UAV structural flexibility in high-precision payload transport missions.

Tables 3 and 4 summarize the comparative evaluation of existing morphing UAV mechanisms with respect to their structural characteristics and control strategies. Table 3 highlights the design aspects, including actuation methods, morphing capabilities, and associated mechanical complexities, while Table 4 focuses on the corresponding control approaches, emphasizing stability, adaptability, and computational demand.

Table 3. Control of significant morphing applications.

Control Method	Target Morphing Type	Strategy	Projects
Open-loop Feedforward Control	Simple camber or span morphing	Predefined actuator inputs based on flight phase	SADE [53]
PID-based Feedback Control	Twist, sweep, folding morphing	Proportional-Integral-Derivative control using sensor feedback	GNATSpar [60]
Adaptive Control	Variable camber, twist	Gain-scheduling, real-time parameter estimation	SMA-actuated [25]
Model Predictive Control (MPC)	Multi-axis morphing (twist + span)	Prediction-based control with constraint handling	SARISTU [54]
Aeroelastic Feedback Control	Camber and leading-edge morphing	Closed-loop using aeroelastic deformation sensors	ACTE [73]
Data-driven/AI-based Control	All morphing types (future scope)	Reinforcement learning, neural networks	SOPHIE [40]
Optimal Control/MDO-based	Mission-driven morphing configuration	Optimization of shape & control inputs jointly	MDO-505 [67]
Model-free cascade PID	the Sarrus linkage platform	PX4 autopilot for position control	Sarrus [23]
Nonlinear Model-Predictive Control	Biaxial propeller tilting	Optimization-based feedback control	QuadPlus [42]
Feedforward	Passively folding	Pixracer R15 flight controller, with PX4 autopilot	FLIFO [49]
Hybrid Control	Wing/airfoil morphing	LQR + PI-FF + ESO, ANFIS scheduling	UAS-S45 [77]
Fuzzy Controller	Spanning approximately 20% to 65% of the chord length	Lyapunov-based robust adaptive laws	UAS-S4 [66]
High-level supervisory controller	Variable wingspans and sweep angles	Predefined lookup tables used to retune for each morphing configuration	Navion L-17 [76]

Table 4. Performance comparison of controllers.

Morphing Type	Controller (As Reported)	Experimental Validation?	Notes	Ref.
Sarrus linkage, single DOF	Cascade PID (arm + flight)	Yes (in-flight morphing)	Controller compensates geometry transitions.	[23]
Biomimetic claw-type multi-link	Servo torque regulation, parallelogram structure	Yes (lab demo)	Stable transition with claw-like grasping capability.	[24]
Four-bar bicopter (MorphoCopter)	Fixed-gain PID; torque-based leverage from tilted props	Yes (morphing transition test)	Tilting props restore roll control in narrow form.	[34]
Soft body morphing (SOPHIE)	Reinforcement Learning/Quasi-static model	Partial (lab scale)	Soft structure demands learning-based feedback.	[40]
Biaxial propeller tilting (QuadPlus)	Cascade control + NMPC	Yes/Simulation	NMPC aids recovery under actuator saturation.	[42]
Rotating frame for payload balance	Adaptive control with real-time parameter estimation	Yes (grasp + drop demo)	Adjusts CG/inertia dynamically during morphing.	[43]
Dual morphing arm (prismatic + revolute)	Lagrangian dynamics, torque-based control	Yes (sim + lab)	Achieves hover with 3 rotors post-failure.	[45]
Flip-triggered passive morphing (FLIFO)	Feedforward controller, PX4-based	Yes (112 transitions)	Uses predefined flip; switches actuator matrices.	[49]
Telescopic + sweep morphing (UAS-S4)	Fuzzy + Lyapunov-based adaptation	No	Broad span change (20–65%); only simulated, no mechanical validation.	[66]
Variable span & sweep (Navion L-17)	Lookup table-based supervisory gain scheduling	Yes (HIL + flight tests)	Lacks adaptive learning; stability achieved through retuning.	[76]
Wing/airfoil morphing	Hybrid: LQR + PI-FF + ESO, ANFIS scheduling	Yes (validated to MIL-STD)	Gain scheduling handles nonlinear dynamics.	[77]
Morphing in narrow environments (segmented)	Constraint-following nonlinear controller + RLS estimator	Yes (sim + flight test)	Robust to disturbances; safety bounds enforced.	[80]
Inward folding quad (span morphing)	PID (position) + PD (attitude) with morphing-aware inertia updates	Yes (wind & trajectory tests)	Control gain adaptation based on morphing angle.	[82]
MEWC-FC + Morphing-state dependent controller	RL (PPO) + PSO for zero-shot generalization	Simulation	Bidirectional control loop; robust under morphology variation.	[83]
Passive morphing with Pixhawk	Off-the-shelf ArduPilot PID	Yes (350+ flights)	Controller unmodified; morphing has mild effect on dynamics.	[85]
Morphing trajectory + landing comparison	RL vs. MPC (control benchmark)	Yes	RL superior under faults; MPC better angular control.	[87]
Continuously variable-length arms	PSO-tuned Sliding Mode Controller	No (simulation only)	Outperforms PID, but no Lyapunov proof or lab validation.	[88]
Dual-mode (QuadRotary)	Lyapunov attitude + cascaded position controller	Yes (lab test)	Magnet-assisted hinges + actuator-free morphing; energy efficiency boosted in rotary mode.	[89]
Multi-mode morphing	Geometric tracking controller on SE(3), Lyapunov-stable	Yes (real-time morphing)	Handles full morphing states without switching control laws.	[90]
Servo-actuated arms with fixed-gain PID	Cascaded PID, empirically tuned	Yes (performance limited)	Responsive within morphing limits; degraded control at large configuration changes.	[91]
Overactuated: tilting rotor UAV (Quad3DV)	Quaternion-based feedback linearization	Yes (simulation)	Redundant rotor control allocation with smooth large-angle handling.	[92]

Morphing UAV controllers reported in the literature employ a variety of formal stability tools. Geometric/nonlinear controllers commonly provide Lyapunov-based proofs

of exponential or almost-global stability on $SE(3)$, which directly handle large attitude errors and time-varying inertial properties. Segmented or gain-scheduled controllers often use uniform-ultimate-boundedness arguments to bound tracking error during morphology transitions, while adaptive controllers and disturbance observers are analyzed within an input-to-state stability framework to quantify robustness to model uncertainty and external disturbances. Where data-driven methods (e.g., reinforcement learning) are used, authors typically complement empirical validation with safety envelopes or fallback model-based controllers to ensure asymptotic or bounded behavior during online operation.

3. Future Prospects and Discussion

Although substantial progress has been made in the development of morphing UAVs, there remains significant potential for exploring novel reconfiguration strategies through the use of advanced mechanical systems. Mechanisms such as four-bar Grashof linkages, ISCMs, parallelogram linkages, as well as spatial and spherical linkages, can offer promising opportunities to enhance structural adaptability and multifunctional capabilities for the morphing quadrotors. These architectures can be tailored to meet specific mission requirements, yet each of them demands a dedicated mathematical modeling framework based on its kinematic complexity, particularly in cases involving spatial or spherical motion systems [8].

3.1. Emerging Trends and Future Directions in Morphing UAV Control Systems

Although recent studies have begun to incorporate advanced control strategies—such as RL, NMPC, and constraint-following approaches—morphing UAVs still demand tighter integration between physical reconfiguration and autonomous decision-making. Future systems are likely to be hybrid, combining model-based robustness with learning-based adaptability.

- **Trend 1: Reinforcement Learning (RL)**

Despite demonstrated robustness and adaptability (e.g., Proximal Policy Optimization in [83]), RL controllers still face barriers to deployment due to real-time computation needs and safety certification hurdles. However, zero-shot generalization to unseen morphologies is a promising path.

- **Trend 2: Coordinated Morphing-Flight Control Loops**

Bidirectional architectures (where morphing state affects flight control and vice versa) are gaining traction. These systems improve responsiveness but require morphology-aware observers and robust estimation under dynamic uncertainty.

- **Trend 3: Stability-Proven Nonlinear Controllers**

The move toward Lyapunov-based, geometric tracking, and constraint-following controllers offers guaranteed robustness during time-varying morphology. Reference controllers like in [79,85,89] highlight mathematically rigorous frameworks.

- **Trend 4: Real-Time Adaptive and Segmented Modeling**

Segmented control frameworks ([84]) model dynamic changes in inertia and CoG in real-time and adapt trajectory tracking accordingly. These approaches do not need full prior knowledge and can adapt to actuator or morphology faults.

- **Trend 5: Morphing-Aware AI + Physics Fusion**

Future control strategies may blend model-based design with physics-informed neural networks or hybrid optimization (e.g., MPC + RL) for mission-specific autonomy. Experimental validation in narrow-space navigation and cluttered environments is key for future work.

3.2. Key Current Limitations

- Actuation Energy and Structural Weight

Morphing mechanisms (e.g., Skygauge, QuadPlus) require multiple actuators, which strain battery life and limit payload—this trade-off restricts scalability and swarm integration.

- Lack of Real-World Validation

Many designs (e.g., UAS-S4, PSO-SMC [85]) remain simulation-only. The absence of real-time control under disturbances hinders transition from lab to field.

- Aeroelastic and Fatigue Challenges

Continuous deformation (e.g., in compliant wing designs) introduces dynamic flutter, fatigue, and uncertainty in control surface performance.

- Limited Bidirectional Integration

Mechanical morphing and control are often developed in isolation. Co-design is needed, especially for whole-body morphing designs like SQUEEZE or FLIFO.

3.3. Research Gaps & Future Directions:

Despite the diversity in morphing architectures, most existing platforms are limited by actuation complexity, high energy demands, and the lack of scalable, real-time control systems. Particularly, the absence of real-world testing in dynamic environments (e.g., wildfire suppression zones) restricts their operational readiness. Future research should focus on co-optimization strategies, integrated sensing, and morphology-aware AI frameworks. Future designs must jointly consider actuator limits, weight constraints, and controller robustness across the entire morphing envelope. Current morphing UAVs are rarely tested under gusts, temperature extremes, or low-pressure environments (e.g., wildfire zones), which is crucial for real-world deployment. Few platforms (e.g., M4) explore swarm-aware morphing. Future studies should enable distributed coordination where morphing enhances swarm behavior (e.g., dynamic formation resizing). Using telemetry-driven decision-making, UAVs should autonomously decide when and how to morph based on terrain, obstacle density, or payload stability.

In this section, a prospective morphing mechanism is introduced alongside a conceptual application scenario. Swarms of quadcopters are increasingly being considered for tasks such as wildfire suppression [96,97], where rapid deployment and efficient operation are critical. However, conventional quadrotors face limitations when attempting to spray fire suppressant mid-flight due to reduced air density and elevated temperatures near the fire front in wildfire zones [98]. Morphing quadcopters can offer a promising solution by enabling dual-mode functionality: an aerial mode for rapid transport and a terrestrial mode for stable ground-based suppression. A schematical design utilizing an ISCM is illustrated in Figure 26A, showing the quadrotor in its frontal flight configuration. Each arm integrates an ISCM, where point C denotes the mounting location of the brushless motors and propellers. During the morphing sequence, the ISCM repositions point C toward the opposite end of its trajectory, as shown in Figure 26B. This motion enables the propellers to retract into a rim structure, which is mounted on and rotates with the output link, as depicted in Figure 27. The CAD model demonstrates the integrated morphing layout in Figure 27, resulting in a compact and aerodynamically optimized configuration during transport or standby modes. This design approach aligns with current research trends emphasizing the co-optimization of mechanical structure and flight control, as seen in recent studies on overactuated and reconfigurable UAV platforms.

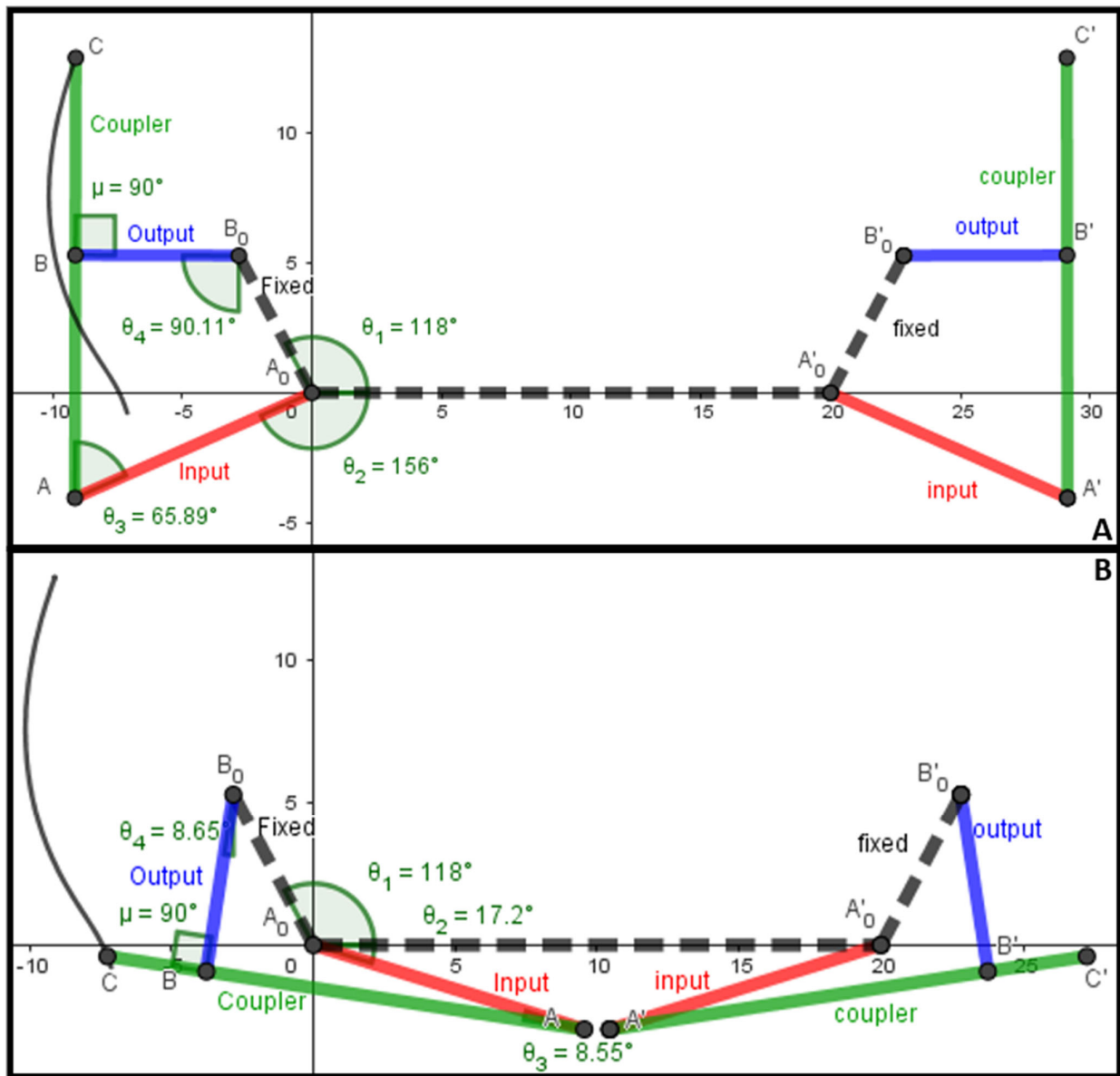


Figure 26. Schematic prospective ISCM where A, B, A₀, B₀ are the joints of the mechanism and C is the coupler point; (A) Frontal view of aerial configuration of ISCM, (B) Frontal terrestrial configuration of ISCM for morphing quadcopters.

Wildfire suppression demands rapid aerial deployment and immediate, efficient intervention to prevent uncontrollable spread. However, the extreme thermal environment near active fire zones significantly reduces air density, impairing rotor efficiency and increasing energy consumption for conventional multirotor UAVs. Drones operating in high-temperature, low-density air conditions experience a decrease in thrust-to-power ratio, resulting in shorter flight endurance and reduced payload capacity [99]. To overcome these limitations, morphing UAVs capable of transitioning from aerial to terrestrial modes can offer a promising solution. By reconfiguring into ground vehicles upon reaching proximity to the fire zone, these systems can maintain operational stability, reduce power consumption, and carry heavier suppression payloads.

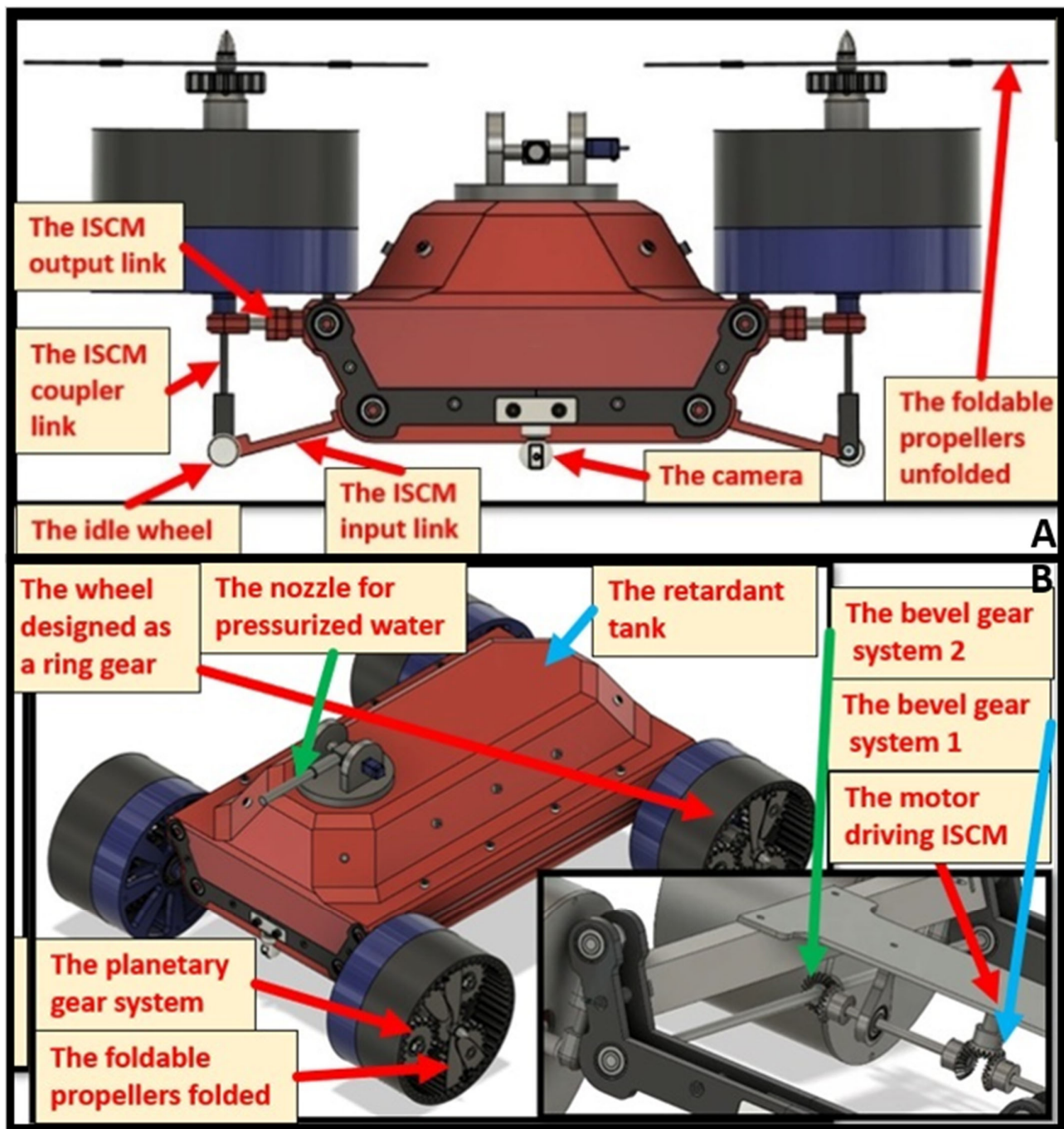


Figure 27. The two modes of conceptual CAD design of morphing quadcopter; (A) Aerial mode, (B) Terrestrial mode.

When deployed in swarm configurations, such morphing drones could collaboratively suppress fires at early stages, coordinating real-time monitoring and intervention while minimizing human risk. This dual-mode capability aligns with recent research trends emphasizing adaptive reconfiguration and cooperative control in UAV swarm applications for complex, hazardous environments. This vehicle could be designed with a modular special tank and modular battery as in [100–102] to swap quickly at a station when they are empty for increment of operation duration and light weight frame [103] to prevent high load caused by components of the vehicle.

The review presents a comprehensive summary of recent developments in morphing quadrotor UAVs, identifying recurring themes and critical divergences in mechanism

design and control integration. A central observation is the persistent trade-off between mechanical complexity and morphing versatility. Mechanisms such as the Sarrus linkage [23] and four-bar-based MorphoCopter [34] demonstrate structural elegance and rapid transformation using minimal actuation. In contrast, biomimetic and overactuated platforms [24,45,90] offer higher adaptability at the expense of weight, control burden, and manufacturing complexity.

Across the reviewed systems, mechanisms with closed kinematic loops generally achieve more symmetric morphing and maintain better inertia balance, which simplifies control during transition. Designs based on open-loop morphologies (e.g., M4 robot [36] and Voliro hexacopter [39]) enable multimodal mobility but face increased uncertainty in real-time control due to asymmetrical deformation. The evolution from purely geometric reconfiguration (e.g., arm length or rotor tilt) to functionally transformative platforms (e.g., quadrotor-blimp hybrids [41]) marks a shift toward mission-driven morphology, aligning with emerging needs in complex environments such as wildfire zones.

Control architectures also exhibit divergence. While conventional PID frameworks (e.g., Pixhawk-based FLIFO [49]) remain surprisingly robust under passive morphing, they fall short in handling high-speed transitions or aggressive maneuvers. More advanced solutions such as Sliding Mode Control, Reinforcement Learning, and Model Predictive Control offering superior adaptability and precision [80,83,88], but are limited by computational load and the need for accurate system identification. Notably, Reinforcement Learning-based controllers show promise in managing nonlinear, uncertain, and time-varying dynamics, but often lack real-world validation and face challenges in deployment without retraining.

Another emerging pattern is the co-design of mechanics and control. Designs like Skygauge [8] and QuadPlus [42] integrate actuation constraints into the control loop to maximize system efficiency and stability. This coupling between structure and software points to a future direction where control-aware morphology becomes a standard design criterion, particularly for applications involving contact-based interaction, narrow-gap traversal, or terrain adaptation.

Despite the significant progress reviewed, several critical gaps remain. Most morphing UAVs are evaluated under ideal laboratory conditions, with limited insight into long-term wear, fault tolerance, or environmental resilience. Likewise, few studies address multi-agent swarm coordination under dynamic reconfiguration, which is vital for collective missions like fire suppression [96,97]. Moreover, the lack of standardized metrics for morphing speed, energy consumption, and control degradation under geometry change makes cross-study comparisons difficult.

In sum, the field is advancing toward more intelligent and versatile UAVs, but achieving robust, field-deployable morphing systems requires bridging the gap between theoretical control development, mechanical prototyping, and real-world mission constraints. The conceptual design proposed in this review—featuring an ISCM—offers a forward-looking pathway for overcoming several of these limitations. Unlike traditional morphing mechanisms that focus solely on shape reduction or thrust reallocation, the ISCM enables dual-mode operation, allowing the quadrotor to function as both an aerial vehicle and a terrestrial platform. This dual functionality directly addresses operational challenges in high-risk environments such as wildfire zones, where elevated temperatures and low air density reduce rotor efficiency and compromise flight endurance. By transitioning to a ground mode upon arrival, the UAV can maintain stability, conserve energy, and operate suppression tools more effectively.

The ISCM facilitates this transformation through a compact rotary layout, wherein the propellers are mounted on a retractable rim structure actuated by a crank-slider assembly.

During morphing, the crank's rotation repositions the propeller base along a predefined path, allowing the rotors to fold inward into the vehicle's central structure. This design not only minimizes aerodynamic drag in standby or ground mode but also enables safe handling, packaging, or docking operations. Furthermore, the modular design of the platform—featuring interchangeable battery packs and fluid tanks—supports extended mission durations through automated swapping mechanisms, making it particularly suited for deployment in UAV swarms operating around a base station. Future iterations of this concept could integrate planetary gear reduction systems for terrain locomotion, enabling more precise torque control during land-based suppression operations.

From a control perspective, the ISCM's symmetric and deterministic motion path simplifies dynamic modeling, offering a stable morphing trajectory that is easier to integrate into onboard controllers. However, successful implementation will require the development of morphology-aware control algorithms that adapt to shifting inertia tensors and propulsion vector changes during transition. The design's emphasis on mechanical simplicity—via a single-actuated transformation—also facilitates fault detection and low-latency response in emergency retraction scenarios, which is a vital feature in mission-critical operations like fireline deployment. Overall, the ISCM-based concept not only addresses current performance and endurance constraints but also reflects broader research trends emphasizing mechanical modularity, adaptive control, and energy-aware reconfiguration in the next generation of UAVs.

4. Conclusions

Despite ongoing advancements in morphing quadrotor design, several key research challenges remain open for exploration. First, the integration of novel mechanical morphing mechanisms—such as inverted slider-crank assemblies, compliant structures, and spatial or spherical linkages—requires dedicated mathematical modeling frameworks that can accommodate nonlinear, time-varying kinematics, particularly during transitional phases. Current literature largely lacks comprehensive design methodologies for such reconfigurable architectures. Second, dynamic modeling and control of morphing platforms continues to present difficulties, especially under overactuation and during configuration shifts. Most existing control strategies, including PID-based and geometric controllers, struggle with parameter uncertainties and disturbance rejection in morphing states. Advanced methods such as feedback linearization, adaptive control, and reinforcement learning show promise, but require further validation under real-time morphing conditions. Third, aerodynamic efficiency and power consumption in low-density environments—such as those encountered in wildfire zones—remain poorly quantified, with current systems exhibiting reduced thrust and increased energy demands. The development of energy-aware morphing strategies, capable of switching between aerial and terrestrial modes, may address these issues but introduces new challenges in mobility, control stability, and mechanical durability. Lastly, the scalability of morphing designs to swarm applications, particularly for time-sensitive missions like fire suppression or confined-space inspection, calls for cooperative control algorithms that can adapt to heterogeneous configurations within the swarm. Addressing these interconnected challenges will be essential for the realization of intelligent, mission-adaptive UAV systems.

5. Patents

Some part of the conceptual design in this paper is under patent investigation with the file number 2025/007853 by Turkish Patent Institution. The patent filing (file no. 2025/007853) pertains to the mechanical ISCM concept and not to the control strategies surveyed here.

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