drones

Review

Morphing Quadrotors: Enhancing Versatility and Adaptability in Drone Applications—A Review

Siyuan Xing [1], Xuhui Zhang [1,*], Jiandong Tian [1,2], Chunlei Xie [1], Zhihong Chen [1] and Jianwei Sun [3,*]

1 China Academy of Aerospace Science and Innovation, Beijing 100088, China; htxsy@126.com (S.X.); tianjd@msn.com (J.T.)
2 College of Engineering, Peking University, Beijing 100871, China
3 Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
* Correspondence: zhangxh0215@126.com (X.Z.); sunjianwei@ciomp.ac.cn (J.S.)

Abstract: The advancement of drone technology has underscored the critical need for adaptability and enhanced functionality in unmanned aerial vehicles (UAVs). Morphing quadrotors, capable of dynamically altering their structure during flight, offer a promising solution to extend and optimize the operational capabilities of conventional drones. This paper presents a comprehensive review of current advancements in morphing quadrotor research, focusing on morphing concept, actuation mechanisms and flight control strategies. We examine various active morphing approaches, including the integration of smart materials and advanced actuators that facilitate real-time structural adjustments to meet diverse mission requirements. Key design considerations—such as structural integrity, weight distribution, and control algorithms—are meticulously analyzed to assess their impact on the performance and reliability of morphing quadrotors. Despite their significant potential, morphing quadrotors face challenges related to increased design complexity, higher energy consumption, and the integration of sophisticated control systems. The discussion on challenges and opportunities highlights the necessity for ongoing advancements in morphing quadrotor technologies, particularly in addressing adaptive control problems associated with highly nonlinear and dynamic morphing aircraft systems, and in the potential integration with smart materials. By synthesizing the latest research and outlining prospective directions, this paper aims to serve as a valuable reference for researchers and practitioners dedicated to advancing the field of morphing quadrotor technologies.

Keywords: morphing quadrotors; adaptive drones; morphing mechanisms; flight control

check for updates

Citation: Xing, S.; Zhang, X.; Tian, J.; Xie, C.; Chen, Z.; Sun, J. Morphing Quadrotors: Enhancing Versatility and Adaptability in Drone Applications—A Review. *Drones* **2024**, *8*, 762. https://doi.org/10.3390/drones8120762

Academic Editor: Abdessattar Abdelkefi

Received: 20 October 2024
Revised: 29 November 2024
Accepted: 11 December 2024
Published: 16 December 2024

1. Introduction

Quadrotors, a widely used type of unmanned aerial vehicle (UAV), have attracted considerable attention from researchers due to their affordability, high maneuverability, and broad operational capabilities [1]. These versatile platforms have proven effective across numerous applications, including disaster relief, infrastructure inspection, and logistics [2–5]. Despite their success in open environments [6], conventional quadrotors are typically designed with a rigid frame where the four motors and propellers are fixed in position. While this design supports stable flight in unobstructed areas, it significantly limits the UAV's ability to maneuver through complex, constrained environments, such as narrow passages or obstacle-dense regions [7,8]. While smaller quadrotors can navigate constrained spaces, their reduced size often comes at the expense of payload capacity, stability, and endurance. Morphing quadrotors aim to address these limitations by dynamically reconfiguring their geometry during flight, enabling optimized navigation and performance in diverse operational scenarios.

Many natural flyers, such as birds, possess the capability to dynamically alter their wing shapes to adapt to changing aerodynamic conditions and environments [9–11]. Inspired by these natural flyers, engineers have sought to emulate their efficiency and adaptability, driving the development of morphing technologies for UAVs, wherein the aircraft's shape or configuration can be altered during flight to enhance performance [12,13]. Morphing quadrotors, in particular, modify their airframe geometry, introducing additional degrees of freedom to optimize speed, agility, and maneuverability in diverse terrains and operational scenarios [7,14]. Despite these advantages, morphing designs face several challenges, including increased mechanical complexity, higher energy consumption for actuation, added weight, and potential compromises in structural robustness. Addressing these challenges requires balancing performance gains with practical design and implementation constraints.

The concept of altering the shape or geometry of aerial vehicles is not new; fixed-wing aircraft have long utilized wing morphing to enhance aerodynamic efficiency and improve flight control [13,15]. Applying this concept to quadrotors—where the relative positions and orientations of the propellers are dynamically modified during flight—represents a recent and innovative research focus. Morphing quadrotors' ability to adapt to varying flight conditions and operate in environments where traditional fixed-configuration UAVs encounter limitations makes them promising candidates for missions requiring high adaptability, such as navigating cluttered spaces or performing in unpredictable conditions [16].

Although there have been numerous reviews on general UAV technologies [13,17,18], there is a lack of comprehensive analysis on how morphing technology, combined with the latest developments in actuators and control strategies, can address these challenges. This work fills this gap by focusing exclusively on morphing quadrotors, examining their dynamic reconfiguration capabilities, the impact of advanced actuators, and corresponding control strategies. By narrowing the scope to these aspects, this review provides a foundation for future research to advance UAV performance across various applications.

This paper is structured as follows: Section 2 explores fundamental morphing concepts in quadrotor design, outlining key principles and configurations that enable dynamic shape transformations during flight, and examines the various actuation mechanisms—including servo motors, linear actuators, and advanced materials—that facilitate these transformations. Section 3 discusses control strategies for morphing quadrotors, focusing on control systems that maintain stability during structural changes. Section 4 addresses the challenges and opportunities in the field, discussing current limitations and potential future developments. Finally, Section 5 summarizes the main findings and implications for future UAV research.

2. Morphing Mechanics and Actuation

2.1. Overview of Morphing Mechanics in Quadrotors

Morphing in quadrotors refers to the dynamic modification of the vehicle's structure during flight, allowing the drone to adapt to various tasks and environmental conditions [14,19], improve aerodynamic efficiency [20], and extend functionality by accommodating additional operational requirements [21]. An example of morphing is demonstrated in the DJI Inspire series, where the drone adjusts the relative position of the camera and rotor plane to facilitate smoother landings and provide an unobstructed field of view for upward or panoramic shots. Figure 1a shows an extended tilt range of up to +100 degrees when the landing gear is lowered, while Figure 1b depicts the unobstructed pan range when the landing gear is raised, which shows how morphing can deliver practical benefits in commercial applications, improving functionality and user experience.

Morphing configurations in quadrotors generally fall into two main categories: in-plane morphing and out-of-plane morphing, which enhance flight performance by optimizing factors such as flight speed, stability, and maneuverability. In-plane morphing focuses on horizontal adjustments, such as changing the rotor distances or their orientations to improve aerodynamics and agility. Out-of-plane morphing involves structural changes perpendicular to the horizontal plane, such as the vertical positioning of components, to enhance lift and control. In addition to flight performance improvements, morphing mechanisms can extend the functional capabilities of quadrotors during missions. For example, some configurations enable drones to grasp objects or carry cargo, making them suitable for specialized roles like object handling or transportation. By integrating adaptive structural designs, morphing quadrotors can perform complex missions that rigid-frame designs cannot achieve.

Figure 1. DJI Inspire 3 in (**a**) camera tilt range extended to +100 degrees when landing gear is lowered; (**b**) unobstructed pan range when landing gear is raised [21].

2.2. Morphing Concepts

2.2.1. In-Plane Morphing

In-plane morphing refers to structural changes within the rotor plane of a quadrotor, which can involve adjustments to the frame angles or the lengths of the arms. This type of morphing significantly influences the drone's aerodynamic properties, moment of inertia, and maneuverability. Unlike traditional fixed-frame quadrotors, in-plane morphing enables the drone to dynamically alter its configuration mid-flight, enhancing its ability to navigate through narrow environments, increase agility, and optimize flight performance.

Variable-length frames refer to a quadrotor design where the length of the arms connecting the rotors to the main body can be dynamically adjusted during flight. By extending or retracting the arms, the quadrotor modifies the relative positions of the rotors, thereby altering its size, aerodynamic profile, and flight characteristics. For example, shortening the arms reduces the moment of inertia, making the quadrotor more agile and better suited for navigating tight spaces. Conversely, extending the arms increases stability and improves wind resistance, which is particularly advantageous in open or turbulent environments. This flexibility is a cornerstone of in-plane morphing, enabling the quadrotor to adapt its morphology based on the demands of the task or environment. To illustrate, Zhao et al. (2017, 2021) [22,23] introduced a quadrotor with variable-length arms, allowing for dynamic adjustments of rotor positions during flight (Figure 2a). This design enhances agility in compact configurations and stability in extended configurations. As shown in Figure 2d, Wang et al. (2024) [24] further developed this concept by incorporating a single linear actuator to create a reconfigurable frame, achieving size reductions of up to 24.4%. However, the practical implementation of such designs introduces challenges, including increased mechanical complexity and the need for advanced control algorithms to manage dynamic shifts in the center of gravity and aerodynamic forces.

Beyond mere size adjustments, morphing quadrotors are also being developed to extend their functionality. Wu et al. (2023) [25] introduced the ring rotor, a retractable quadrotor that not only alters its arm length but also incorporates a grasping capability for transporting objects without additional manipulators. The ring design creates a flexible grasping area, enhancing functionality for tasks such as object handling or cargo transportation (Figure 2b,c). Similarly, Xu et al. (2024) [26], inspired by an eagle's claw, developed a biomimetic morphing quadrotor with a multi-link structure that allows the arms to fold vertically for dynamic grasping mid-flight, providing enhanced adaptability for navigating narrow spaces or performing complex tasks (Figure 2e). These advanced designs highlight the potential for morphing quadrotors to perform dual roles, such as flight and manipulation, broadening their scope beyond traditional UAV applications. Kornatowski et al. (2020) [27] also adopted a bio-inspired approach, designing a morphing quadrotor inspired by the box turtle. This features retractable arms that fold into a protective cage during takeoff and landing, reducing risks to nearby humans. When extended, the arms optimize stability and efficiency.

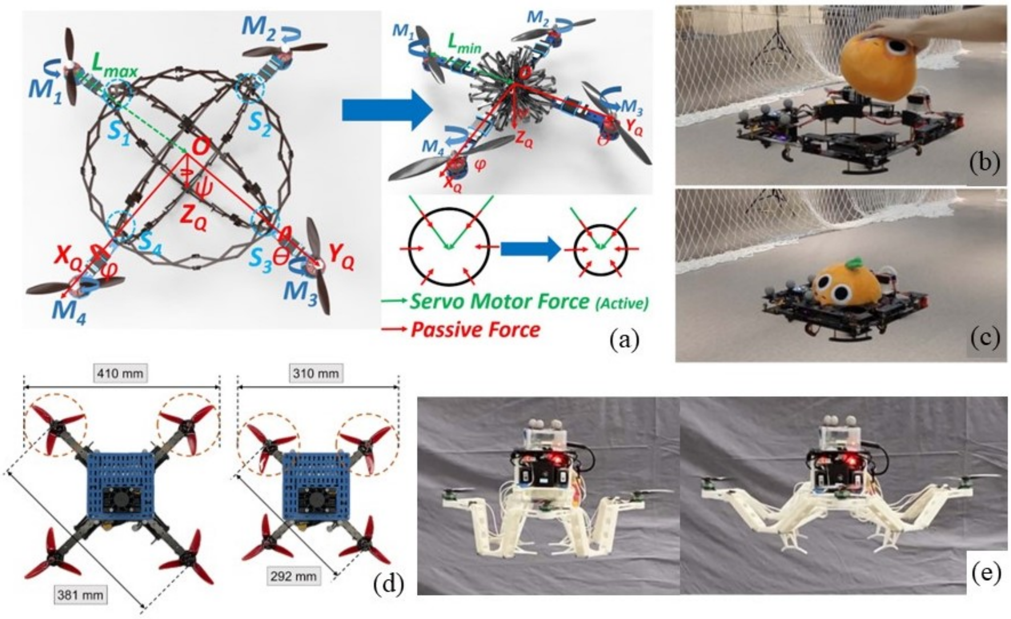


Figure 2. In-plane morphing via variable-length arms. (**a**) The off-center scissor structure is designed using angulated elements to create a variable curvature, allowing for a variable-length arm configuration. The scissor-like design enables the arms to contract or extend by altering the angle of its interconnected elements, dynamically changing the quadrotor's overall size during flight [22]. In (**b**), the quadrotor is shown in its expanded state for general flight, while (**c**) illustrates the contracted state where the ring structure wraps around an object (a doll) to grasp it securely without requiring additional robotic arms [25]. (**d**) Top view of the morphing quadrotor UAV at both maximum and minimum configurations, incorporating a reconfigurable frame based on the Sarrus linkage mechanism [24]. (**e**) The quadrotor's arms can fold vertically to facilitate dynamic grasping, emulating the transition of an eagle's claw from an open to a closed position [26].

Another type of in-plane morphing involves adjusting the frame angle, which can alter both rotor configuration and flight performance [14,20,28–32]. The X-Morf quadrotor by Desbiez et al. (2017) [29] features a scissor-joint mechanism that allows the arms to fold mid-flight, reducing the wingspan by 28.5% within 0.5 s (Figure 3d). Mechanical adjustment enables the quadrotor to navigate confined spaces efficiently while maintaining structural integrity. The lightweight design allows for rapid reconfiguration without adding significant complexity, making it highly adaptable to obstacle-dense environments. Furthermore, as shown in Figure 3a–c, Falanga et al. (2019) [14] introduced a foldable morphing quadrotor capable of dynamically altering its configuration mid-flight. While Desbiez's design adjusts the frame angle to enhance crash resilience and morph in-flight, Falanga's quadrotor adds the ability to fold its arms independently. This foldable morphing quadrotor can morph into specific configurations—such as "X", "T", "O", or "H"—depending on the flight condition, to adapt to specific tasks such as flying through narrow gaps. The design incorporates four independently rotating arms that fold around the main frame, with an optimal control strategy ensuring stable flight regardless of the drone's changing morphology.

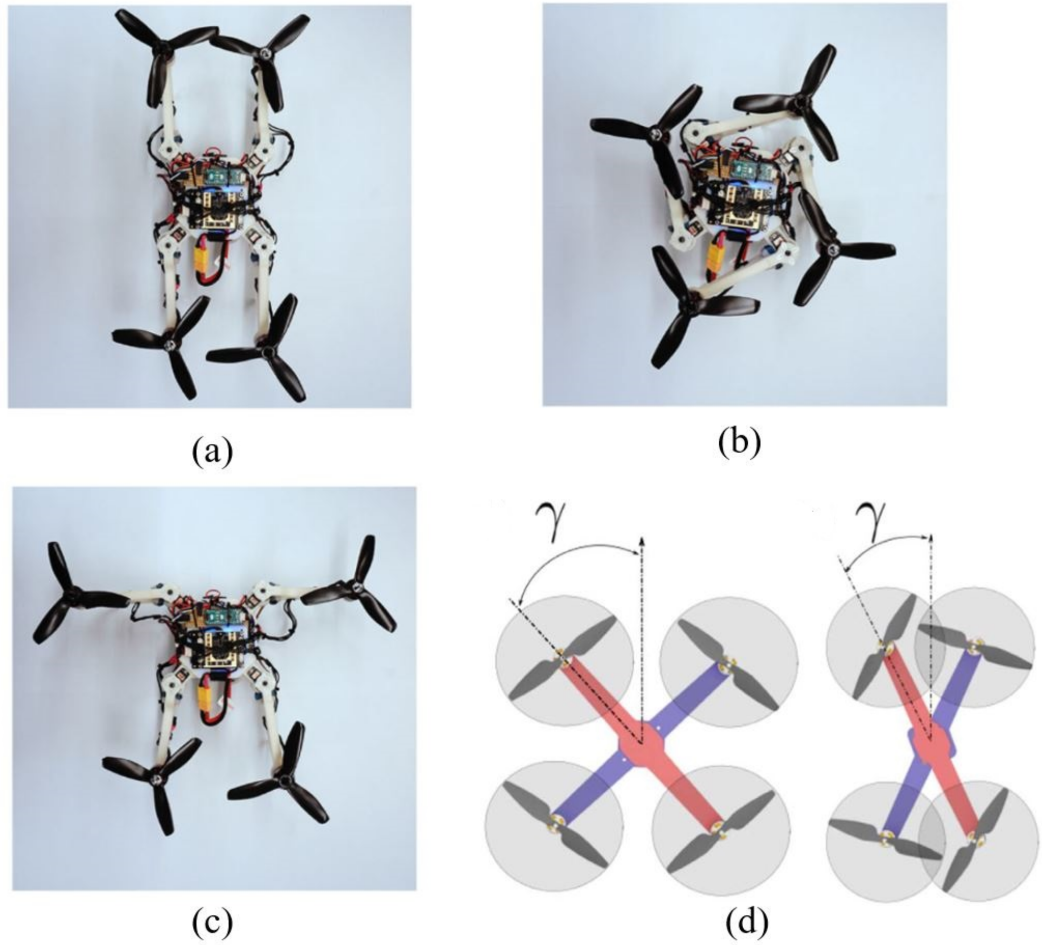


Figure 3. Quadrotor with morphofunctional folding capabilities, demonstrating the ability to transition between various configurations to adapt to specific tasks [14]. (**a**) H configuration; (**b**); O configuration (**c**); T configuration. (**d**) X-Morf robot's morphing principle, illustrating a span reduction by decreasing the scissor–joint angle between its arms from 90° to 60°, enabling efficient reconfiguration for varying operational needs [29].

The foldable design leads to more time being taken for morphing. Riviere et al. (2018) [30] focused on rapid and seamless morphing for high-speed navigation in cluttered environments (Figure 4d [30]). They extended the concept of dynamic frame adjustment by introducing an elastic folding mechanism. This Quad-Morphing robot is equipped with a scissor-like structure that allows it to fold its arms swiftly, reducing its wingspan by 48% to pass through narrow apertures at high speeds. The elastic structure enables the quadrotor to dynamically adjust its frame mid-flight, allowing for smooth transitions without aggressive maneuvers.

Adjusting rotor positions through frame angle modifications introduces significant challenges related to variations in the center of gravity (CoG), which are more complex compared to symmetrical arm length adjustments. Notably, Kim et al. (2021) [20] introduced a novel morphing quadrotor system that estimates payload weight, CoG, and inertia tensor in real time, dynamically adjusting its configuration for optimal flight performance (Figure 4e–h). This adaptive approach significantly improves flight stability when handling variable payloads by autonomously determining the ideal morphology for efficient operation. Similarly, Avant et al. (2018) [31] proposed a morphing quadrotor that adjusts both arm orientation and length to maintain flight stability, even in the event of rotor failure. By leveraging the morphing capability, the quadrotor redistributes forces to compensate for the failed rotor, highlighting how real-time structural reconfiguration can enhance hover stability under challenging conditions.

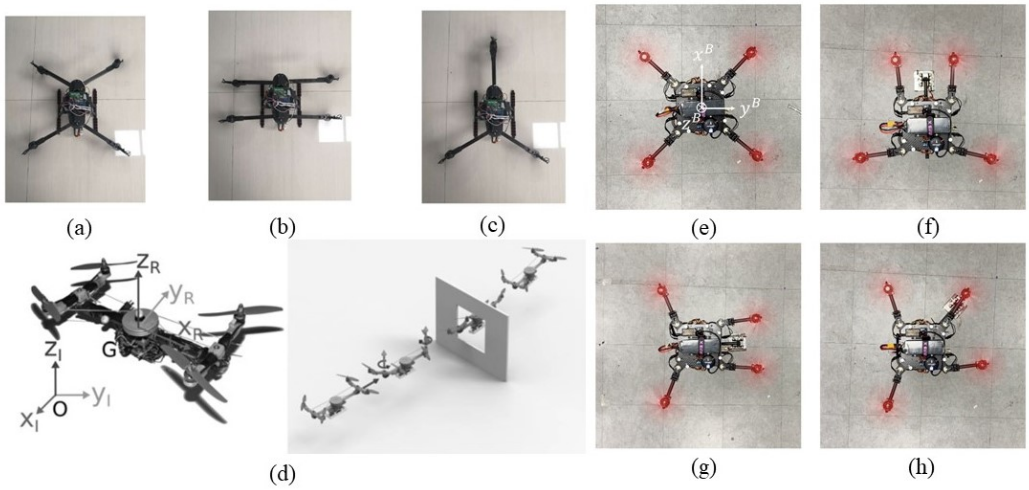


Figure 4. Morphing in-plane through variable arm angles. The morphing quadrotor is shown in (**a**) the conventional X configuration, (**b**) the H configuration, and (**c**) the inverted Y configuration [32]. (**d**) Agile robotic fliers [30]. (**e**–**h**) The morphing quadrotor with a 1 kg payload mounted at different positions: (**e**) at $x = 0$ cm, $y = 0$ cm; (**f**) at $x = +15$ cm, $y = 0$ cm; (**g**) at $x = 0$ cm, $y = +15$ cm; and (**h**) at $x = \frac{15}{\sqrt{2}}$ cm, $y = \frac{15}{\sqrt{2}}$ cm [20].

To address the propeller diameter limitations that restrict the range of frame angle adjustments, Hu et al. (2021) [32] proposed a novel morphing quadrotor design where the arms are positioned in different planes, allowing the rotors to overlap (Figure 4a–c), which maximizes the quadrotor's width compression ratio, enabling it to fly through narrow gaps while reducing the impact of overlapping rotors on lift efficiency. By placing the rotors alternately on the top and bottom sides of the arms, the design minimizes interference and maintains lift performance despite the reduced space. Based on these two concepts, Derrouaoui et al. (2020) [33] proposed a new quadrotor that can alter both the arm length and the arm frame angle using eight servo motors. In addition, they presented a detailed and generic model for three possible cases: (1) the extension of the arms, (2) the rotation of the arms, and (3) the hybridization between the extension and rotation of the arms.

2.2.2. Out-of-Plane Morphing

Out-of-plane morphing involves altering the rotor configuration in three-dimensional space, enabling enhanced maneuverability and control by dynamically adjusting thrust directions. This approach significantly expands the capabilities of quadrotors, allowing them to execute advanced maneuvers, navigate complex environments, and perform precision tasks in dynamic scenarios. Research on out-of-plane morphing can be categorized into two major approaches: rotor tilt mechanisms and synchronized morphing systems.

Rotor tilt mechanisms focus on dynamically adjusting the rotor angles relative to the drone's frame during flight. These designs introduce additional degrees of freedom, enabling fine-tuned control for position, orientation, and trajectory adjustments. For example, Ryll et al. (2015) [34] introduced a quadrotor equipped with servo motors that tilts rotors perpendicular to the arms (Figure 5a). This configuration enhances agility and enables advanced flight maneuvers, making it suitable for applications requiring precise orientation adjustments. In contrast, Badr et al. (2016) [35] proposed an arm-aligned tilt mechanism (Figure 5b), which decouples translational and rotational movements. This design improves stability for tasks such as horizontal hovering with minimal inclination and is advantageous in constrained environments. More advanced designs, such as the TiltDrone by Zheng et al. (2020) [36] and the QuadPlus by Singh et al. (2022) [37], incorporate biaxial rotor tilting for superior control. These mechanisms allow thrust vectoring along both pitch and roll axes, enabling complex maneuvers and navigation through dense or cluttered environments (Figure 5c).

Synchronized morphing systems focus on simplifying the control of rotor tilting while maintaining enhanced maneuverability. These systems often rely on coordinated adjustments to multiple rotors, reducing the number of actuators required and streamlining control complexity. Odelga et al. (2016) [38] proposed a parallelogram-based tilting mechanism that uses two actuators to simultaneously adjust all four rotors, providing dynamic thrust direction control with reduced mechanical complexity. Similarly, Ryll et al. (2016) [39] introduced the FAST-Hex, a hexacopter capable of transitioning between underactuated and fully actuated modes using a single motor to tilt all rotors in unison. This design demonstrates a balance between energy efficiency and precision, highlighting the advantages of synchronized tilting mechanisms in simplifying morphing implementation (Figure 5d).

The trend in out-of-plane morphing focuses on either increasing degrees of freedom for greater flexibility or simplifying the design to enhance reliability and reduce mechanical complexity. For instance, TiltDrone and QuadPlus emphasize dual-axis tilting for tasks requiring precise hover angles or operation in uneven environments, offering increased maneuverability. Conversely, systems like Odelga's parallelogram mechanism and the FAST-Hex minimize actuator requirements to simplify control while maintaining performance.

While out-of-plane morphing provides unparalleled adaptability, it also presents significant challenges in terms of flight stability, energy efficiency, and the complexity of control algorithms. Future advancements will need to address these issues to fully realize the potential of these systems for real-world applications. As research advances, the development of more robust control systems will be key to unlocking the full potential of out-of-plane morphing in quadrotors.

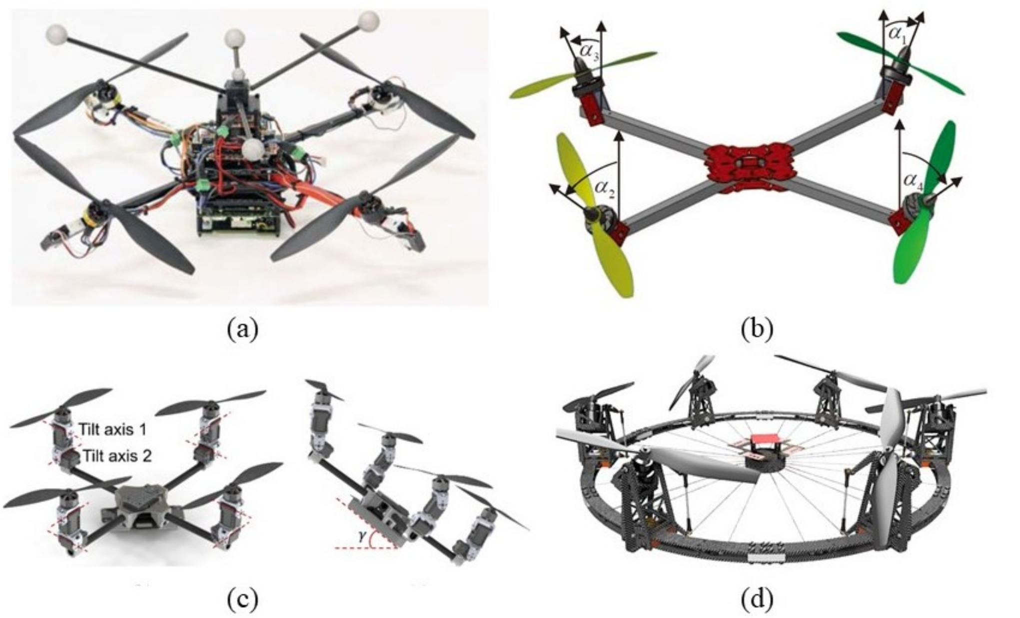


Figure 5. Out-of-plane morphing quadrotors. (**a**) Quadrotor tilting around the frame arm, demonstrating out-of-plane morphing capabilities [34]; (**b**) quadrotor tilting along the frame arm, enabling morphing beyond the horizontal plane [35]; (**c**) illustration of the two tilting axes for each propeller, showcasing biaxial tilting for hovering in a hyperplane at an arbitrary angle γ relative to the horizontal plane [37]; (**d**) the hexarotor fully actuated by synchronized tilting (FAST-Hex), a design where six propellers are actively tilted using a single additional servomotor, achieving advanced out-of-plane morphing [39].

2.2.3. Other Concepts for Enhanced Functionality

Several innovations in morphing quadrotors have focused on enhancing functionality beyond conventional designs. As shown in Figure 6, Zhao et al. (2017) [40] pioneered the concept of whole-body aerial manipulation, wherein the entire structure of a transformable multirotor, equipped with two-dimensional multi-links, morphs into a large gripper. This capability allows for stable and precise object handling mid-flight, eliminating the need for separate manipulator arms. Building upon this concept of integrated manipulation, Zhao et al. (2018) [41] advanced this trajectory with the DRAGON aerial robot, which incorporates multi-degree-of-freedom transformation through a dual-rotor-embedded multi-link structure. The extendable system enables dynamic shape changes during flight, offering full pose control and allowing the quadrotor to perform advanced aerial maneuvers, including navigating through narrow spaces.

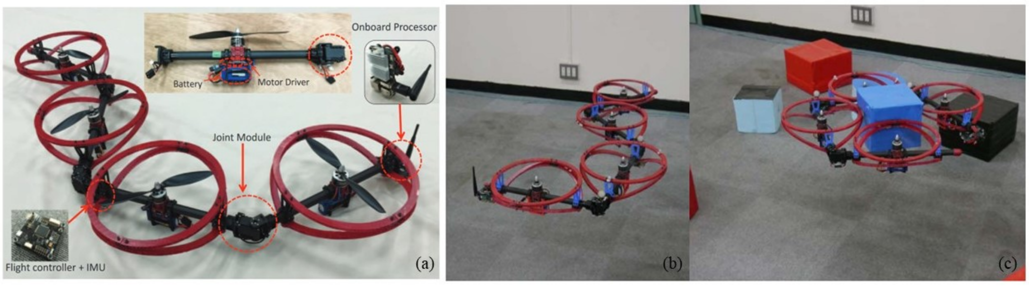


Figure 6. (**a**) Hardware components of the prototype, consisting of four links; (**b**) the multirotor equipped with two-dimensional multi-links, enabling aerial transformation; (**c**) whole-body aerial manipulation demonstrated by the transformable aerial robot [40].

Recently, Sharma et al. (2024) [42] introduced the Janus platform, a hybrid quadrotor-blimp system designed for ecological sensing. Janus not only extends flight duration through its blimp mode but also seamlessly transitions to quadrotor mode within 0.36 s in case of balloon failure, illustrating the trend of integrating multiple functionalities into morphing designs (Figure 7). To extend functionality, Zheng et al. (2023) [43] proposed a metamorphic aerial robot inspired by gliding mammals, employing a tendon-driven system that enables mid-air shape morphing for rapid perching. The evolution from simple morphing to bio-inspired solutions enhances the quadrotor's ability to navigate complex environments by reducing mass and increasing agility in cluttered spaces.

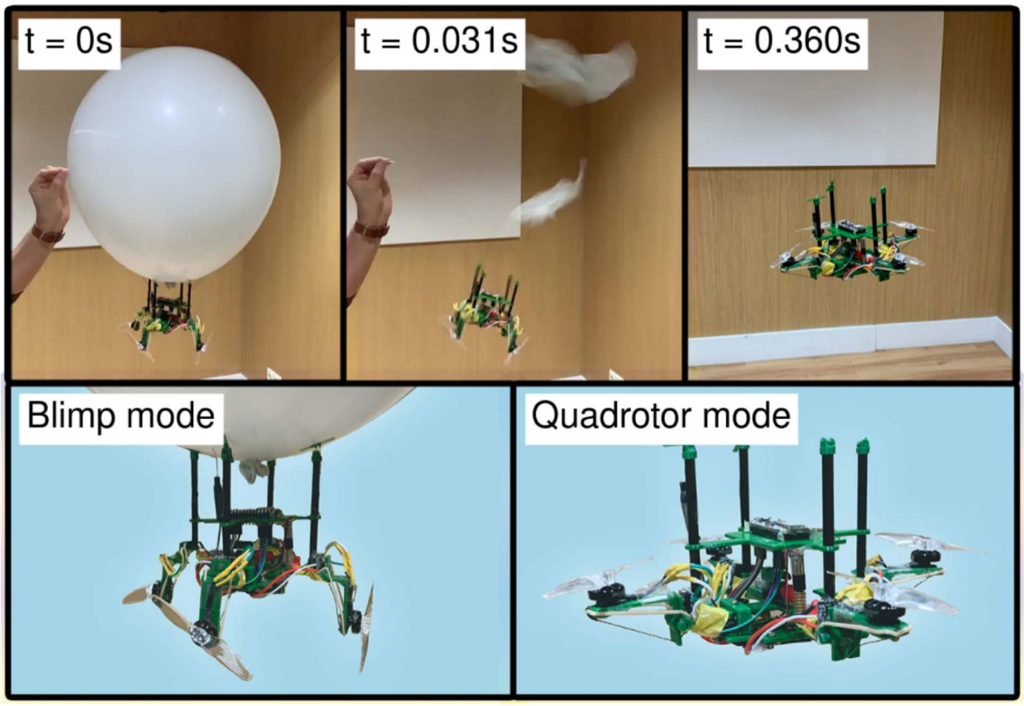


Figure 7. The Janus prototype shown in blimp mode detecting balloon failure and transitioning into quadrotor mode [42].

Overall, these examples demonstrate the progressive enhancement of morphing technologies, where each innovation introduces more integrated, adaptive, and biomimetic functionalities. By enabling tasks such as whole-body manipulation, hybrid propulsion, rapid perching, and full-pose control, morphing quadrotors are increasingly pushing the boundaries of versatility and operational capability in aerial robotics.

2.3. Actuation Mechanisms

2.3.1. Types of Actuators

In morphing quadrotors, actuation mechanisms primarily rely on servo motors to facilitate dynamic structural transformations [14,20,28–32,34]. A critical aspect of these systems is actuator stiffness, which ensures that the structure remains stable and locked in the desired position after morphing. This stiffness of frame structure is essential for maintaining flight stability, particularly in designs that involve significant morphing during flight [17].

In both in-plane and out-of-plane morphing designs, servo motors are widely used to control changes in rotor configuration, facilitating structural adjustments that enhance both agility and stability during flight. Even with reduced degrees of freedom—such as designs that limit actuation to two axes [29,30,38]—morphing systems can effectively navigate through constrained spaces. More minimalistic approaches, such as employing a single linear actuator or servo motor to drive a linkage mechanism, have also proven effective in enabling changes in rotor axis distance [24,25,39]. These efficient structural adjustments have reduced mechanical complexity, indicating that fewer actuators can still support significant morphing functionality.

Beyond traditional servo motors and linear actuators, emerging smart materials are being investigated to further advance actuation mechanisms. Technologies such as Soft Pneumatic Actuators [44] and Shape Memory Alloys (SMAs) [45] present promising alternatives to conventional actuators. Smart materials offer the potential for more flexible, lightweight, and energy-efficient morphing systems, thereby increasing the adaptability of morphing quadrotors in complex environments. As research into these materials progresses, they may provide enhanced capabilities for morphing aerial vehicles by reducing weight while maintaining performance and flexibility.

2.3.2. Integration with Structural Components

The integration of morphing mechanisms into quadrotor structures necessitates a trade-off between the flexibility required for shape transformations and the structural strength essential for stable flight. Morphing quadrotors must undergo dynamic reconfigurations without compromising their aerodynamic performance or structural integrity, making the choice of materials and actuation mechanisms critical.

In passive morphing systems [46–49], the focus is on minimizing mechanical complexity while enabling real-time shape alterations. For example, some designs incorporate rotary joints and sprung hinges, allowing the arms to fold and unfold in response to thrust without additional actuators [47]. This simple structure reduces weight while ensuring that shape changes are responsive and controlled. Materials such as carbon fiber, which provides both flexibility for morphing and rigidity to withstand aerodynamic forces, are commonly used. Similarly, foldable quadrotors utilize torque generated by the propellers to passively deploy within seconds [50]. Lightweight materials like fiberglass and Icarex fabric are employed to maintain structural strength during flight while enabling compact folding for easy storage and transport.

In active morphing systems, actuators such as servo motors are embedded within the structure to actively change the arm length or rotor configuration. The most common method involves placing servo motors in morphing joints. For example, Xu et al. (2024) [26] implemented retractable arms using servos and 20 links, allowing dynamic length adjustments while maintaining structural strength (Figure 8). Furthermore, retractable arms driven by servos [41] or belt-drive systems [51] adjust the rotor positions and center of gravity, ensuring enhanced stability and agility during flight. Soft actuators, such as Soft

Pneumatic Actuators (SPAs) [44], are also being explored to integrate flexible materials with traditional fixed-frame configurations, enabling a balance between structural flexibility and control (see Figure 9). Furthermore, Bai and Chirarattananon (2022) [45] introduced SplitFlyer Air, a quadcopter that disassembles into two bicopters mid-flight using Shape Memory Alloy (SMA)-triggered undocking mechanisms. These approaches, while promising, must address challenges related to aerodynamics and energy consumption to achieve efficient morphing.

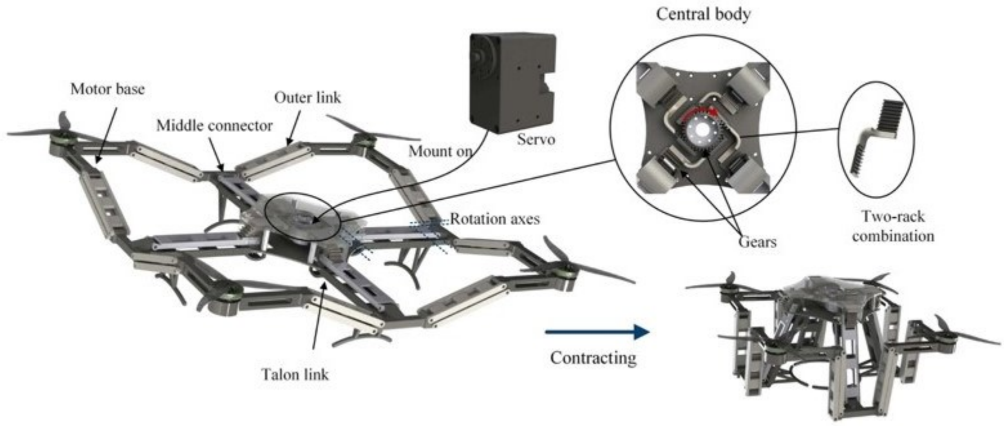


Figure 8. Overview of the morphing quadrotor design, consisting of 20 links: talon links, middle connectors, outer links, and motor bases. The frame is a symmetrical, closed-loop structure, with the talon link serving as an arm mounted on a rotating base with two rotation axes [26].

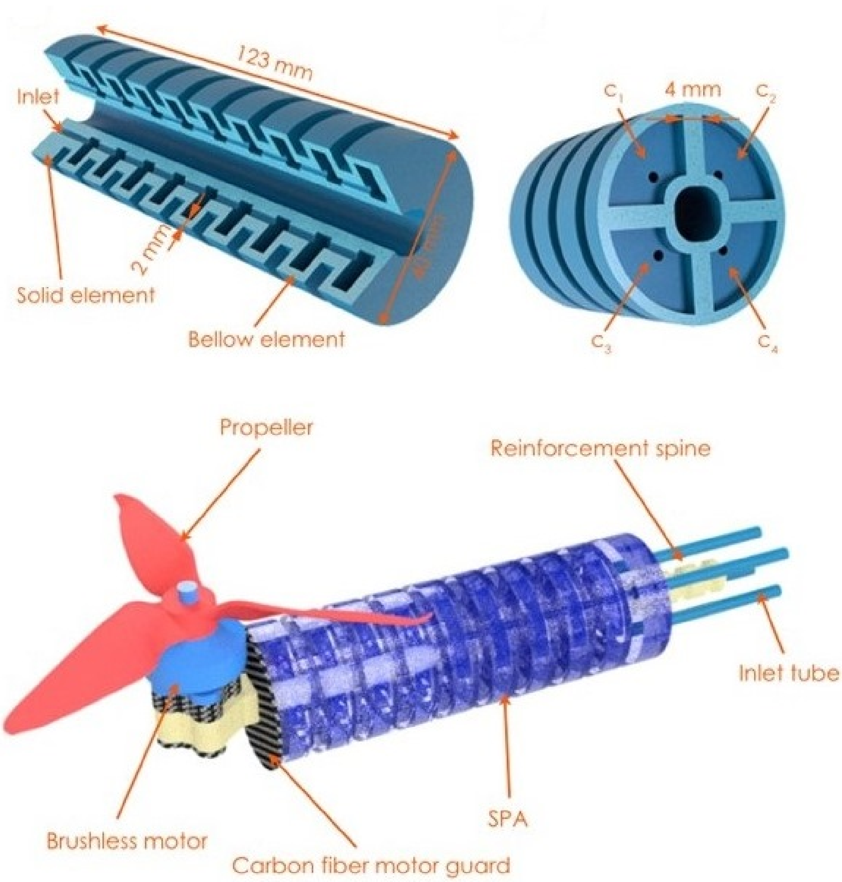
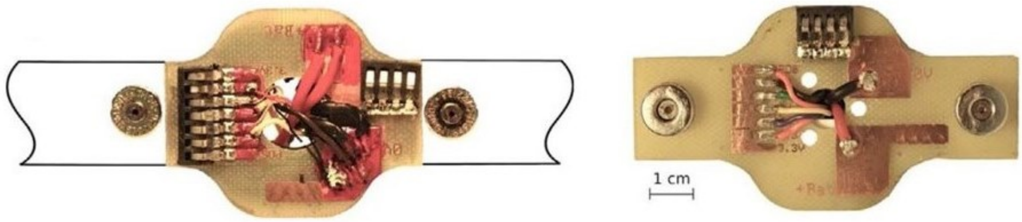


Figure 9. Radial and transverse plane cross-sections of the Soft Pneumatic Actuator (SPA), highlighting the inner structure's chambers, along with the complete assembly of a quadrotor arm incorporating the SPA [44].

The successful integration of morphing mechanisms also depends on the strategic placement of joints, hinges, and electronic components [29,50,52]. Electrical connections at key joints facilitate seamless transitions between configurations, ensuring smooth morphing without compromising structural integrity. Similarly, passive hinge systems allow for rapid deployment, while sensors and control units embedded within the structure enable real-time monitoring and flight adjustments. Achieving a delicate balance between the flexibility required for shape transformations and the structural integrity needed for stable flight is essential in the integration of morphing mechanisms into quadrotor structures. Careful placement of actuation components and the use of real-time control systems are crucial for ensuring that aerodynamic performance and structural stability are maintained throughout the morphing process (Figure 10).



(a) (b)

Figure 10. Magnetic docking mechanism. The top and bottom images show the docking components of the upper arms. (**a**) The printed circuit board (PCB) and magnets directly attached to the upper arm. (**b**) The PCB with complementary magnets secured to the upper section of the scissor joint [29].

3. Control Strategies

3.1. Modeling and Challenges in Controlling Morphing Quadrotors

To understand the complexities of morphing quadrotor control, it is essential to first analyze the basic dynamics of a conventional quadrotor. The rigid-body equations of motion for a standard quadrotor can be expressed as follows:

$$\dot{x} = v, \tag{1}$$
$$m\dot{v} = mg\mathbf{e}_3 - f\mathbf{R}\mathbf{e}_3, \tag{2}$$
$$\dot{\mathbf{R}} = \mathbf{R}\hat{\Omega}, \tag{3}$$
$$\mathbf{J}\dot{\Omega} = -\Omega \times \mathbf{J}\Omega + \tau, \tag{4}$$

where $x \in \mathbb{R}^3$ represents the position of the quadrotor's center of mass in the inertial frame, $v \in \mathbb{R}^3$ is the velocity, $\mathbf{R} \in SO(3)$ is the rotation matrix from the body-fixed frame to the inertial frame, and $\Omega \in \mathbb{R}^3$ denotes the angular velocity in the body frame. Here, m is the vehicle mass, g is the gravitational acceleration, $\mathbf{e}_3$ is the unit vector along the z-axis, $\mathbf{J}$ is the moment of inertia matrix, f is the total thrust generated by the motors, and τ is the torque vector applied to the quadrotor.

In a conventional quadrotor, the thrust and torque are related to the motor speeds via the control allocation matrix A, given by the following:

$$\begin{bmatrix} f \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = A \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix},$$

where ω_i represents the angular velocity of each rotor. For rigid-frame quadrotors, A remains constant. However, in morphing quadrotors, the control allocation matrix A changes dynamically due to structural transformations, such as variable arm lengths or rotor tilts, which introduce new complexities into the control design [17].

Morphing quadrotors face additional challenges as structural transformations affect the center of gravity (CoG) and aerodynamic forces, in addition to the moment of inertia (MoI).

For instance, as the arms extend, the CoG shifts outward, requiring higher torque to generate the same angular acceleration, which affects flight stability and energy efficiency. Conversely, retracted arms bring the CoG closer to the body, improving agility but reducing resistance to external disturbances. These interactions create nonlinearities that demand advanced control strategies to manage both dynamic stability and maneuverability [14,32,53,54].

Traditional control strategies, such as Proportional–Integral–Derivative (PID) control [55,56], are effective for rigid configurations with centrally located fixed payloads but struggle to accommodate the dynamic changes introduced by morphing. To maintain stability during these transformations, the control system must adapt continuously, recalibrating rotor speeds and power distribution in real time while managing dynamic shifts in CoG and MoI.

Advanced control strategies, such as adaptive control [57–59], are particularly suited for morphing quadrotors as they can recalibrate control parameters dynamically in response to changing conditions. Additionally, these algorithms must account for variable control allocation matrices and asymmetries, ensuring precise handling of nonlinear flight dynamics during structural transitions. Emerging approaches, such as reinforcement learning-based methods, also show promise in addressing these challenges by enabling autonomous adaptation in complex environments.

3.2. Morphing Quadrotor Control Methods

3.2.1. Adaptive and Robust Control Methods

Traditional UAV control strategies rely on the relationship between the propellers' thrust and the total aerodynamic forces applied to the UAV's body. For rigid vehicles with fixed motors, the inertia matrix remains constant. However, unlike traditional fixed-configuration quadrotor UAVs, morphing leads to an asymmetric configuration, resulting in changes to the inertia matrix [17]. Direct methods attempt to correct the dynamic model in real time to accommodate these changes. For example, Kim et al. [20] proposed a novel method that significantly relaxes restrictions on payload position and weight by using a morphing quadrotor system. This method estimates the drone's weight, center of gravity position, and inertia tensor in real time. However, obtaining the dynamic model of morphing quadrotor UAVs necessitates direct consideration of the effects induced by the morphing angles, which can result in substantial modeling efforts.

In practical systems, the presence of uncertainty is unavoidable and exerts a substantial influence on the system's control performance. Addressing uncertainty has become a critical issue in control systems in recent years. A central approach to managing the dynamic transformations in morphing quadrotors is through adaptive control methods, which continuously update control laws to account for variations in the inertia matrix, mass distribution, and aerodynamic forces. Common control methods for tackling this issue include adaptive sliding mode control [60], adaptive neural sliding mode control [61], and adaptive robust control [62]. In the context of morphing quadrotor control, systems utilizing Linear Quadratic Regulators (LQRs) [63], such as those presented by Falanga et al. (2019) [14], recalculate the moment of inertia and update control gains in real time, ensuring stability during transitions like arm folding or extension. The adaptive feedback loop enables the quadrotor to maintain flight stability despite significant morphological changes.

Additionally, Model Reference Adaptive Control (MRAC) has been employed to address more complex morphing behaviors [64–66]. Patnaik et al. (2023) [66] demonstrated that this method, which adjusts the system based on a reference model that compensates for uncertainties in inertia and aerodynamics, ensures robust stability even during significant shape changes. Further advancing this strategy, Dong et al. (2024) [67] introduced an adaptive robust control framework that segments the quadrotor into subsystems and applies the Udwadia–Kalaba equation to convert flight trajectories into constraints,which enables the quadrotor to adapt in real time while maintaining precise control during structural transformations. Moreover, some morphing designs, such as those with elastic folding mechanisms, present additional control challenges due to rapid, nonlinear changes in rotor configuration. Riviere et al. (2018) [30] demonstrated that adaptive control strategies are crucial in such cases, compensating for temporary instabilities like the momentary loss of roll axis control during folding. Advanced feedback systems stabilize the quadrotor once morphing is complete, allowing it to navigate narrow spaces and perform advanced maneuvers with precision.

3.2.2. Machine Learning Approaches

To enhance control adaptability, recent research has integrated advanced machine learning techniques [19,32,68,69]. Reinforcement Learning (RL)-based control methods have been investigated to enable quadrotors to dynamically adjust their behavior in response to changing configurations. Hu et al. (2021) [32] proposed an extended-state RL algorithm in which controllers adapt to real-time feedback, thereby minimizing control errors and improving the quadrotor's ability to handle complex morphing transitions (Figure 4a–c). Their system employs Deterministic Policy Gradient (DPG) algorithms refined through actor–critic networks, enabling quadrotors to continuously learn and adapt as they encounter new flight conditions. Very recently, Yang et al. (2024) [69] introduced the cc-DRL flight control algorithm for arm-length-varying morphing quadrotors, leveraging a combination of Deep Reinforcement Learning (DRL) and Convex Combination (CC) techniques (Figure 11). Utilizing a model-free Proximal Policy Optimization (PPO) algorithm, they trained optimal flight control laws for representative arm-length modes of the quadrotor. By interpolating these pre-trained control laws, the system dynamically adjusts to various arm configurations, thereby enhancing the adaptability of the quadrotor during morphing. Simulation results demonstrated significant improvements in flight stability and precision. The continued advancement of machine learning approaches, particularly in handling complex dynamics and uncertainties, holds significant promise for further enhancing control strategies of morphing quadrotors, enabling more intelligent and autonomous flight capabilities in increasingly challenging environments. However, updating the pre-trained model remains a challenge in data-driven methods.

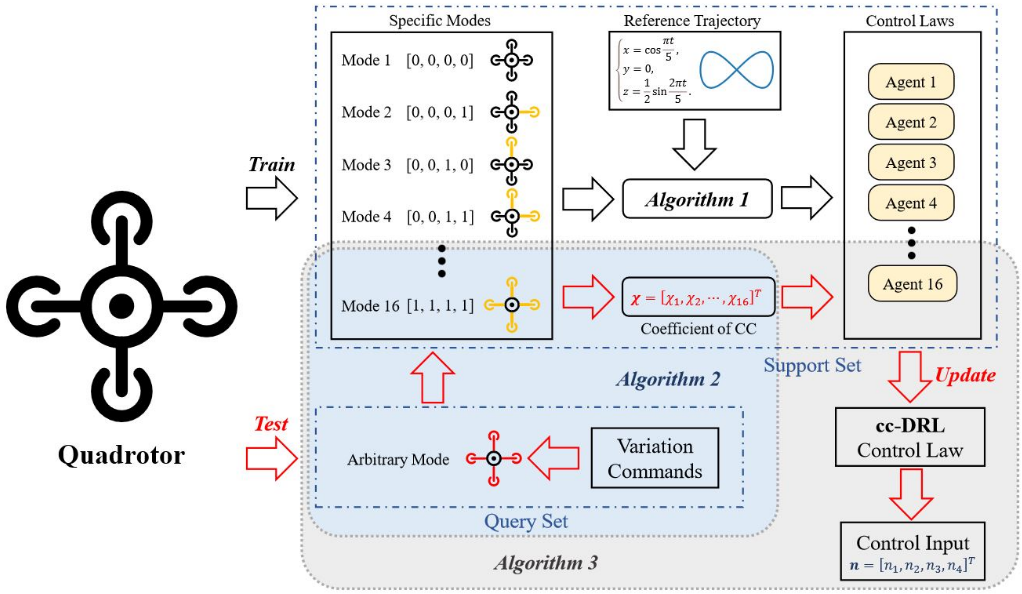


Figure 11. Structure of the proposed cc-DRL flight control algorithm for an arm-length-varying quadrotor [69]. Algorithm 1 illustrates the DRL algorithm used for the offline training of optimal flight control laws for selected representative arm lengths. Algorithm 2 introduces a convex combination method for arbitrary arm lengths, usable online or substituted by an offline pre-trained neural network. Algorithm 3 presents the cc-DRL flight control scheme that receives external length variation commands and updates the combination weights of the trained optimal control laws online to achieve near-optimal flight performance.

3.3. Motion Planning and Trajectory Generation

As introduced earlier, morphing quadrotors can change their geometric structure to navigate through narrow spaces smaller than their size, such as pipes, mines, caves, and other restricted scenarios, by employing integrated actuation mechanisms to fold arms and reduce their dimensions. However, complex dynamics are introduced by morphing pose challenges in motion planning [70], particularly because trajectory planning must consider both the shifting Center of Gravity (CoG) and the attitude adjustments required when navigating narrow passages. Morphing quadrotors offer advantages over traditional designs [14,28,46] by exhibiting greater adaptability to different task scenarios, including traversing narrow gaps, grasping objects [25,26], and transporting payloads [20,27]. While morphing quadrotors with more Degrees of Freedom (DOFs) can achieve more complicated motion planning, studies that consider DOFs in motion planning for morphing quadrotors are limited due to the difficulty associated with uncertainties in quadrotor dynamics.

As shown in Figure 12, Cui et al. (2024) [19] developed a trajectory planning and control system that integrates adaptive strategies to ensure safe and efficient deformations. Their proposed framework utilizes a spatial–temporal trajectory optimizer that accounts for structural changes, enabling quadrotors to generate full-body safety trajectories that include both position and attitude adjustments. This fusion of adaptive control and trajectory planning enhances the quadrotor's ability to deform autonomously while maintaining stability. Beyond trajectory planning, flight functions such as grasping can also be considered in motion planning. These complex functions require highly adaptive motion planning and trajectory generation to achieve more intelligent flight.

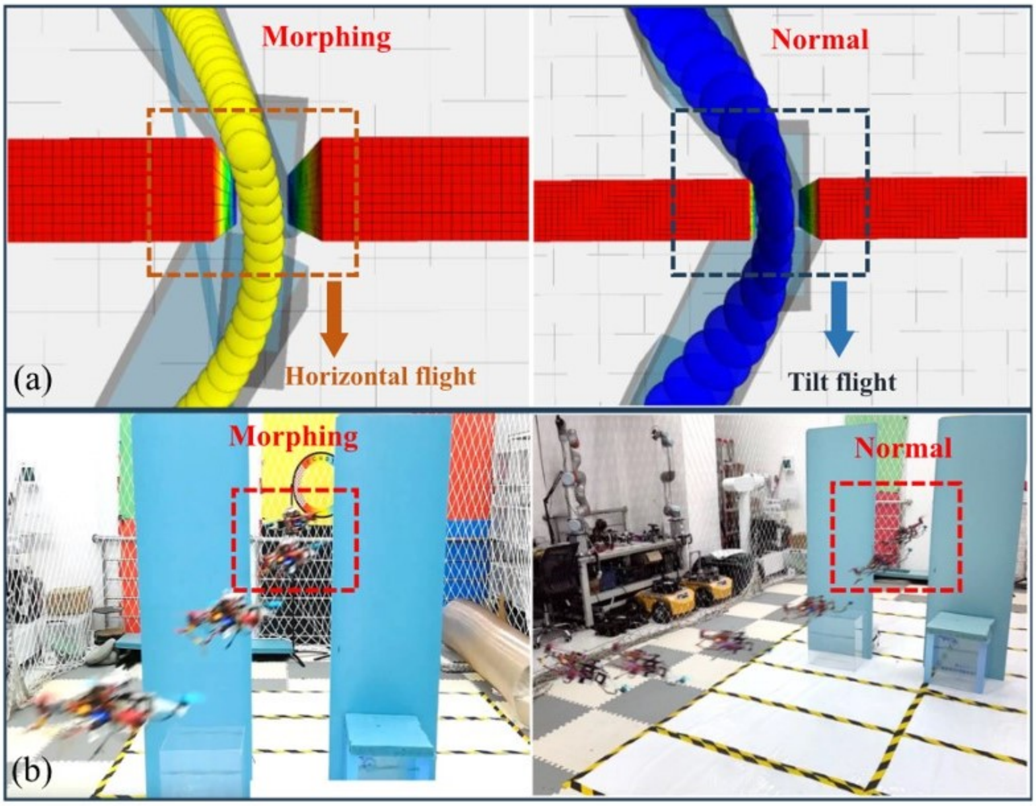


Figure 12. Comparison of quadrotor trajectories through a narrow gap. The ellipsoids represent the position and attitude of the quadrotor. (**a**) Schematic diagram (**b**) Experimental photographs. [19].

4. Challenges and Opportunities

Current developments in morphing quadrotors involve addressing a series of complex challenges, particularly in mechanical design and control strategies. Appendix A summarizes recent studies on morphing quadrotors. These challenges and opportunities can be broadly categorized into mechanical and control aspects.

In terms of mechanical design, morphing quadrotor systems face the challenge of balancing flexibility and structural integrity. The ability to adapt shape while maintaining the strength required to withstand aerodynamic forces is critical. Materials used in morphing frames must be flexible enough for deformation yet rigid enough to handle mechanical loads during high-speed maneuvers. Additionally, actuation systems such as servo motors, linear actuators, and Soft Pneumatic Actuators (SPAs) [44,71] increase the system's weight, negatively affecting payload capacity and power efficiency. Furthermore, achieving lightweight designs often necessitates trade-offs between material durability and mechanical performance, which may limit operational lifespan in demanding conditions. Active systems like servo-driven morphing often require locking mechanisms to ensure stability, leading to higher power consumption and reduced flight endurance. These challenges highlight the need for lightweight, energy-efficient materials and actuation systems. On the opportunity front, advances in smart materials [72], such as those that change shape or stiffness in response to external stimuli, could reduce reliance on heavy actuators. Such materials enable passive or semi-active morphing, improving energy efficiency and flight duration. Moreover, biomimetic designs inspired by energy-efficient flight mechanics of birds and insects [73,74] and morphing blade airfoil [75–77] offer innovative solutions for developing lightweight and efficient morphing mechanisms.

In terms of control, maintaining stability during rapid structural transformations is one of the most critical challenges. Morphing inherently alters the quadrotor's center of gravity (CoG), moment of inertia (MoI), and aerodynamic properties, introducing nonlinearities and asymmetries that complicate flight dynamics. These challenges are further exacerbated when morphing is performed mid-flight under external disturbances, requiring advanced control algorithms capable of real-time compensation for these effects. Current control strategies, such as Linear Quadratic Regulators (LQRs) [14,63] and Model Reference Adaptive Control (MRAC) [64,66], often struggle during rapid transitions and in highly dynamic environments. Integrating sensors and actuators into control systems adds complexity due to the need for real-time adjustments and computational resources. The integration of machine learning methods, such as reinforcement learning (RL)-based control systems [78,79], offers a promising opportunity to handle the nonlinear dynamics of morphing systems. By continuously learning from real-time data and adapting control policies, RL-based systems could provide more robust solutions for managing rapid transformations. Additionally, advancements in sensor fusion and real-time data processing [80–82] could further enhance the stability and autonomy of morphing quadrotors, enabling them to perform complex tasks such as search and rescue, environmental monitoring, and industrial inspections with greater precision and reliability.

5. Conclusions

Morphing quadrotors represent a significant advancement in unmanned aerial vehicle (UAV) technology, particularly for tasks requiring high maneuverability and adaptability in cluttered or constrained environments. This review examined the fundamental morphing concepts in quadrotor design, various actuation mechanisms, and control strategies essential for maintaining stability during morphing. By addressing existing challenges related to mechanical complexity, structural integrity, energy efficiency, and control, the full potential of morphing quadrotors can be realized.

The integration of advanced materials, innovative actuation mechanisms, and sophisticated control strategies is crucial for unlocking new applications, ranging from autonomous search and rescue missions to precise infrastructure inspections. Future research efforts should focus on optimizing these elements to enhance performance, reliability, and operational capabilities. By overcoming current limitations, morphing quadrotors have the potential to become versatile, robust, and invaluable tools across a wide range of fields, thereby pushing the boundaries of what is possible with aerial robotic systems.

Author Contributions: Conceptualization, investigation and writing—original draft preparation, S.X. and J.S.; writing—review and editing, X.Z., J.T., C.X. and Z.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (Grant No. 52192633).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of Morphing Drone Designs with Actuation Concepts, Design Features, and Control Strategies.

Reference	Actuators and Morphing Concept	Design Feature	Control Strategies
Falanga et al. (2019) [14]	4 servo motors; in-plane morphing; weighs 580 g and spans 47 cm tip-to-tip in diagonal configuration	Capable of transitioning between "X", "T", "O", and "H" configurations	Adaptive Linear Quadratic Regulator (LQR) control
Riviere et al. (2018) [30]	2 servo motors; in-plane morphing; weighs 400 g and adjusts from 268 mm unfolded to 128 mm folded wingspan	Reduces wingspan by 48% to navigate through constrained spaces	Proportional-Integral-Derivative (PID) controller
Wang et al. (2024) [24]	1 linear actuator; frame-arm length in-plane morphing; weighs 1250 g and adjusts from 410 mm maximum to 310 mm minimum size	Arm length decreases by 24.4%, enabling adaptation to dynamic environments during flight	PID controller
Xu et al. (2024) [26]	1 servo motor; frame-arm length in-plane morphing; weighs 1250 g and adjusts frame size from 48.16 cm extended to 38.62 cm folded	Closed-loop multilink structure with talon links mimicking eagle claw morphology for grasping tasks	Cascade adaptive sliding mode control with admittance filter
Singh et al. (2022) [37]	8 servo motors; tilting rotor, out-of-plane morphing; weighs 2.012 kg with arm lengths of 235 mm	Hyperdynamic QuadPlus platform with 12 degrees of freedom (DoF), enabling attitude control independent of position	Nonlinear Model Predictive Control (NMPC)
Hu et al. (2021) [32]	4 servo motors; frame-arm angle in-plane morphing; weighs approximately 1.2 kg with compact adjustable arms	Morphing quadrotor with rotatable arms capable of overlapping to minimize width for passing through narrow gaps	Reinforcement learning (RL) with an extended-state approach
Sharma et al. (2024) [42]	Linear servo; function extension; weighs 159 g (excluding the balloon) and uses 60 cm and 90 cm diameter balloons	Hybrid blimp-drone platform with integrated failure detection and recovery mechanisms for balloon system	Multi-sensor fusion with PID control
Wu et al. (2023) [25]	1 servo motor with slider; frame-arm length in-plane morphing; weighs approximately 1 kg and spans 41.4 cm × 41.4 cm extended, reducing to 28.4 cm × 28.4 cm retracted	Single servo motor reduces vehicle size by 31.4% during flight	Nonlinear Model Predictive Control (NMPC) strategy
Ruiz et al. (2022) [49]	4 servo motors; out-of-plane morphing; weighs approximately 1.8 kg with adjustable arms for dynamic configuration	Quasi-static arm deformations modeled and feedback into the autopilot system	PID controller

Table A1. *Cont.*

Reference	Actuators and Morphing Concept	Design Feature	Control Strategies
Haluska et al. (2022) [44]	Soft Pneumatic Actuators (SPA); bending frame-arm in-plane morphing; weighs 1 kg and measures 490 mm × 490 mm × 130 mm	Soft pneumatic actuated morphing enabling transitions between "X" and "H" configurations	PID controller
Kamel et al. (2018) [83]	6 servo motors; tilting rotor, out-of-plane morphing; weighs 3.2 kg and utilizes tiltable rotors	Hexacopter with tiltable rotors allowing decoupling of position and orientation control	Nonlinear Model Predictive Attitude Control
Desbiez et al. (2017) [29]	1 servo motor; frame-arm angle in-plane morphing; weighs 380 g with an adjustable arm span of 21 cm per arm	X-Morf robot dynamically adjusts arm angles by up to 28.5% during flight, improving stability and attitude tracking	Model Reference Adaptive Control (MRAC)
Kumar et al. (2020) [51]	2 servo motors with belt; frame-arm length in-plane morphing; weighs 1.56 kg with a nominal arm length of 0.25 m	Considers dynamic shifts in center of gravity (CoG) affecting moment of inertia (MoI)	PID controller

References

1. Floreano, D.; Wood, R.J. Science, technology and the future of small autonomous drones. *Nature* **2015**, *521*, 460–466. [CrossRef] [PubMed]
2. Sun, J.; Yuan, G.; Song, L.; Zhang, H. Unmanned Aerial Vehicles (UAVs) in Landslide Investigation and Monitoring: A Review. *Drones* **2024**, *8*, 30. [CrossRef]
3. Tomic, T.; Schmid, K.; Lutz, P.; Domel, A.; Kassecker, M.; Mair, E.; Grixa, I.L.; Ruess, F.; Suppa, M.; Burschka, D. Toward a fully autonomous UAV: Research platform for indoor and outdoor urban search and rescue. *IEEE Robot. Autom. Mag.* **2012**, *19*, 46–56. [CrossRef]
4. Nex, F.; Remondino, F. UAV for 3D mapping applications: A review. *Appl. Geomat.* **2014**, *6*, 1–15. [CrossRef]
5. Jordan, S.; Moore, J.; Hovet, S.; Box, J.; Perry, J.; Kirsche, K.; Lewis, D.; Tse, Z.T.H. State-of-the-art technologies for UAV inspections. *IET Radar Sonar Navig.* **2018**, *12*, 151–164. [CrossRef]
6. Klavins, E.; Zagursky, V. Unmanned aerial vehicle movement trajectory detection in open environment. *Procedia Comput. Sci.* **2017**, *104*, 400–407. [CrossRef]
7. Delmerico, J.; Mintchev, S.; Giusti, A.; Gromov, B.; Melo, K.; Horvat, T.; Cadena, C.; Hutter, M.; Ijspeert, A.; Floreano, D.; et al. The current state and future outlook of rescue robotics. *J. Field Robot.* **2019**, *36*, 1171–1191. [CrossRef]
8. Silvagni, M.; Tonoli, A.; Zenerino, E.; Chiaberge, M. Multipurpose UAV for search and rescue operations in mountain avalanche events. *Geomat. Nat. Hazards Risk* **2017**, *8*, 18–33. [CrossRef]
9. Pennycuick, C.J. The flight of birds and other animals. *Aerospace* **2015**, *2*, 505–523. [CrossRef]
10. Bowman, J.; Sanders, B.; Weisshaar, T. Evaluating the impact of morphing technologies on aircraft performance. In Proceedings of the 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, CO, USA, 22–25 April 2002; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2002; p. 1631.
11. Liu, T.; Wang, S.; Liu, H.; He, G. Engineering perspective on bird flight: Scaling, geometry, kinematics and aerodynamics. *Prog. Aerosp. Sci.* **2023**, *142*, 100933. [CrossRef]
12. Ajaj, R.M.; Parancheerivilakkathil, M.S.; Amoozgar, M.; Friswell, M.I.; Cantwell, W.J. Recent developments in the aeroelasticity of morphing aircraft. *Prog. Aerosp. Sci.* **2021**, *120*, 100682. [CrossRef]
13. Barbarino, S.; Bilgen, O.; Ajaj, R.M.; Friswell, M.I.; Inman, D.J. A Review of Morphing Aircraft. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 823–877. [CrossRef]
14. Falanga, D.; Kleber, K.; Mintchev, S.; Floreano, D.; Scaramuzza, D. The Foldable Drone: A Morphing Quadrotor That Can Squeeze and Fly. *IEEE Robot. Autom. Lett.* **2019**, *4*, 209–216. [CrossRef]
15. Chopra, I. Review of state of art of smart structures and integrated systems. *AIAA J.* **2002**, *40*, 2145–2187. [CrossRef]
16. Wallace, D.A. Dynamics and Control of a Quadrotor with Active Geometric Morphing. Ph.D. Thesis, University of Washington, Seattle, WA, USA, 2016.
17. Patnaik, K.; Zhang, W. Towards reconfigurable and flexible multirotors: A literature survey and discussion on potential challenges. *Int. J. Intell. Robot. Appl.* **2021**, *5*, 365–380. [CrossRef]
18. Rashad, R.; Goerres, J.; Aarts, R.; Engelen, J.B.; Stramigioli, S. Fully actuated multirotor UAVs: A literature review. *IEEE Robot. Autom. Mag.* **2020**, *27*, 97–107. [CrossRef]

19. Cui, G.; Xia, R.; Jin, X.; Tang, Y. Motion planning and control of a morphing quadrotor in restricted scenarios. *IEEE Robot. Autom. Lett.* **2024**, *9*, 5759–5766. [CrossRef]
20. Kim, C.; Lee, H.; Jeong, M.; Myung, H. A Morphing Quadrotor that Can Optimize Morphology for Transportation. In Proceedings of the 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Prague, Czech Republic, 27 September–1 October 2021; IEEE: Piscataway, NJ, USA, 2021.
21. DJI. DJI Inspire 3. Available online: https://www.dji.com/inspire-3 (accessed on 19 October 2024).
22. Zhao, N.; Luo, Y.; Deng, H.; Shen, Y. The Deformable Quad-Rotor: Design, Kinematics and Dynamics Characterization, and Flight Performance Validation. In Proceedings of the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, BC, Canada, 24–28 September 2017; IEEE: Piscataway, NJ, USA, 2017.
23. Zhao, N.; Yang, W.; Peng, C.; Wang, G.; Shen, Y. Comparative Validation Study on Bioinspired Morphology-Adaptation Flight Performance of a Morphing Quad-Rotor. *IEEE Robot. Autom. Lett.* **2021**, *6*, 5145–5152. [CrossRef]
24. Wang, Y.; Liu, C.; Zhang, K. A Novel Morphing Quadrotor UAV with Sarrus-Linkage-Based Reconfigurable Frame. In Proceedings of the 2024 6th International Conference on Reconfigurable Mechanisms and Robots (ReMAR), Chicago, IL, USA, 24–27 June 2024; IEEE: Piscataway, NJ, USA, 2024; pp. 283–289. [CrossRef]
25. Wu, Y.; Yang, F.; Wang, Z.; Xu, C. Ring-Rotor: A Novel Retractable Ring-Shaped Quadrotor with Aerial Grasping and Transportation Capability. *IEEE Robot. Autom. Lett.* **2023**, *8*, 2126–2133. [CrossRef]
26. Xu, M.; De, Q.; Yu, D.; Hu, A.; Liu, Z.; Wang, H. Biomimetic Morphing Quadrotor Inspired by Eagle Claw for Dynamic Grasping. *IEEE Trans. Robot.* **2024**, *40*, 2513–2528. [CrossRef]
27. Kornatowski, P.M.; Feroskhan, M.; Stewart, W.J.; Floreano, D. A Morphing Cargo Drone for Safe Flight in Proximity of Humans. *IEEE Robot. Autom. Lett.* **2020**, *5*, 4233–4240. [CrossRef]
28. Fabris, A.; Aucone, E.; Mintchev, S. Crash 2 Squash: An Autonomous Drone for the Traversal of Narrow Passageways. *Adv. Intell. Syst.* **2022**, *4*, 2200113. [CrossRef]
29. Desbiez, A.; Expert, F.; Boyron, M.; Diperi, J.; Viollet, S.; Ruffier, F. X-Morf: A crash-separable quadrotor that morfs its X-geometry in flight. In Proceedings of the 2017 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Linkoping, Sweden, 3–5 October 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 222–227. [CrossRef]
30. Riviere, V.; Manecy, A.; Viollet, S. Agile Robotic Fliers: A Morphing-Based Approach. *Soft Robot.* **2018**, *5*, 541–553. [CrossRef] [PubMed]
31. Avant, T.; Lee, U.; Katona, B.; Morgansen, K. Dynamics, Hover Configurations, and Rotor Failure Restabilization of a Morphing Quadrotor. In Proceedings of the 2018 Annual American Control Conference (ACC), Milwaukee, WI, USA, 27–29 June 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 4855–4862. [CrossRef]
32. Hu, D.; Pei, Z.; Shi, J.; Tang, Z. Design, Modeling and Control of a Novel Morphing Quadrotor. *IEEE Robot. Autom. Lett.* **2021**, *6*, 8013–8020. [CrossRef]
33. Derrouaoui, S.; Bouzid, Y.; Guiatni, M.; Dib, I.; Moudjari, N. Design and Modeling of Unconventional Quadrotors. In Proceedings of the 2020 28th Mediterranean Conference on Control and Automation (MED), Saint-Raphael, France, 16–19 June 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 721–726. [CrossRef]
34. Ryll, M.; Bulthoff, H.H.; Giordano, P.R. A Novel Overactuated Quadrotor Unmanned Aerial Vehicle: Modeling, Control, and Experimental Validation. *IEEE Trans. Control Syst. Technol.* **2015**, *23*, 540–556. [CrossRef]
35. Badr, S.; Mehrez, O.; Kabeel, A. A novel modification for a quadrotor design. In Proceedings of the 2016 International Conference on Unmanned Aircraft Systems (ICUAS), Arlington, VA, USA, 7–10 June 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 702–710.
36. Zheng, P.; Tan, X.; Kocer, B.B.; Yang, E.; Kovac, M. TiltDrone: A fully-actuated tilting quadrotor platform. *IEEE Robot. Autom. Lett.* **2020**, *5*, 6845–6852. [CrossRef]
37. Singh, K.; Mehndiratta, M.; Feroskhan, M. QuadPlus: Design, Modeling, and Receding-Horizon-Based Control of a Hyperdynamic Quadrotor. *IEEE Trans. Aerosp. Electron. Syst.* **2022**, *58*, 1766–1779. [CrossRef]
38. Odelga, M.; Stegagno, P.; Bulthoff, H.H. A fully actuated quadrotor UAV with a propeller tilting mechanism: Modeling and control. In Proceedings of the 2016 IEEE International Conference on Advanced Intelligent Mechatronics, AIM 2016, Banff, AB, Canada, 12–15 July 2016.
39. Ryll, M.; Bicego, D.; Franchi, A. Modeling and control of FAST-Hex: A fully-actuated by synchronized-tilting hexarotor. In Proceedings of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Daejeon, Republic of Korea, 9–14 October 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 1689–1694. [CrossRef]
40. Zhao, M.; Kawasaki, K.; Chen, X.; Noda, S.; Okada, K.; Inaba, M. Whole-body aerial manipulation by transformable multirotor with two-dimensional multilinks. In Proceedings of the 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 29 May–3 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 5175–5182. [CrossRef]
41. Zhao, M.; Anzai, T.; Shi, F.; Chen, X.; Okada, K.; Inaba, M. Design, Modeling, and Control of an Aerial Robot DRAGON: A Dual-Rotor-Embedded Multilink Robot with the Ability of Multi-Degree-of-Freedom Aerial Transformation. *IEEE Robot. Autom. Lett.* **2018**, *3*, 1176–1183. [CrossRef]
42. Sharma, S.; Verhoeff, M.; Joosen, F.; Prasad, R.V.; Hamaza, S. A Morphing Quadrotor-Blimp with Balloon Failure Resilience for Mobile Ecological Sensing. *IEEE Robot. Autom. Lett.* **2024**, *9*, 6408–6415. [CrossRef]
43. Zheng, P.; Xiao, F.; Nguyen, P.H.; Farinha, A.; Kovac, M. Metamorphic aerial robot capable of mid-air shape morphing for rapid perching. *Sci. Rep.* **2023**, *13*, 1297. [CrossRef]

44. Haluska, J.; Vastanalv, J.; Papadimitriou, A.; Nikolakopoulos, G. Soft pneumatic actuated morphing quadrotor: Design and development. In Proceedings of the 2022 30th Mediterranean Conference on Control and Automation (MED), Athens, Greece, 28 June–1 July 2022; IEEE: Piscataway, NJ, USA, 2022.
45. Bai, S.; Chirarattananon, P. SplitFlyer Air: A Modular Quadcopter That Disassembles Into Two Bicopters Mid-Air. *IEEE/ASME Trans. Mechatron.* **2022**, *27*, 4729–4740. [CrossRef]
46. Patnaik, K.; Mishra, S.; Sorkhabadi, S.M.R.; Zhang, W. Design and Control of SQUEEZE: A Spring-augmented QUadrotor for intEractions with the Environment to squeeZE-and-fly. In Proceedings of the 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, NV, USA, 25–29 October 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1364–1370. [CrossRef]
47. Bucki, N.; Mueller, M.W. Design and Control of a Passively Morphing Quadcopter. In Proceedings of the 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019.
48. Fabris, A.; Kirchgeorg, S.; Mintchev, S. A soft drone with multi-modal mobility for the exploration of confined spaces. In Proceedings of the 2021 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), New York, NY, USA, 25–27 October 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 48–54.
49. Ruiz, F.; Arrue, B.C.; Ollero, A. SOPHIE: Soft and Flexible Aerial Vehicle for Physical Interaction with the Environment. *IEEE Robot. Autom. Lett.* **2022**, *7*, 11086–11093. [CrossRef]
50. Mintchev, S.; Daler, L.; L'Eplattenier, G.; Saint-Raymond, L.; Floreano, D. Foldable and self-deployable pocket sized quadrotor. In Proceedings of the 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, USA, 26–30 May 2015; IEEE: Piscataway, NJ, USA, 2015.
51. Kumar, R.; Deshpande, A.M.; Wells, J.Z.; Kumar, M. Flight Control of Sliding Arm Quadcopter with Dynamic Structural Parameters. In Proceedings of the 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, NV, USA, 25–29 October 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1358–1363. [CrossRef]
52. Mintchev, S.; de Rivaz, S.; Floreano, D. Insect-Inspired Mechanical Resilience for Multicopters. *IEEE Robot. Autom. Lett.* **2017**, *2*, 1248–1255. [CrossRef]
53. Derrouaoui, S.H.; Guiatni, M.; Bouzid, Y.; Dib, I.; Moudjari, N. Dynamic Modeling of a Transformable Quadrotor. In Proceedings of the 2020 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 1–4 September 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1714–1719. [CrossRef]
54. Fresk, E.; Nikolakopoulos, G. Full quaternion based attitude control for a quadrotor. In Proceedings of the 2013 European Control Conference (ECC), Zurich, Switzerland, 17–19 July 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 3864–3869.
55. Bouabdallah, S.; Noth, A.; Siegwart, R. PID vs LQ control techniques applied to an indoor micro quadrotor. In Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566), Sendal, Japan, 28 September–2 October 2004; Volume 3, pp. 2451–2456. [CrossRef]
56. Lopez-Sanchez, I.; Moreno-Valenzuela, J. PID control of quadrotor UAVs: A survey. *Annu. Rev. Control* **2023**, *56*, 100900. [CrossRef]
57. Dydek, Z.T.; Annaswamy, A.M.; Lavretsky, E. Adaptive control of quadrotor UAVs: A design trade study with flight evaluations. *IEEE Trans. Control Syst. Technol.* **2012**, *21*, 1400–1406. [CrossRef]
58. Schreier, M. Modeling and adaptive control of a quadrotor. In Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, Chengdu, China, 5–8 August 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 383–390.
59. Islam, S.; Liu, P.; El Saddik, A. Nonlinear adaptive control for quadrotor flying vehicle. *Nonlinear Dyn.* **2014**, *78*, 117–133. [CrossRef]
60. Nguyen, N.P.; Mung, N.X.; Thanh, H.L.N.N.; Huynh, T.T.; Lam, N.T.; Hong, S.K. Adaptive sliding mode control for attitude and altitude system of a quadcopter UAV via neural network. *IEEE Access* **2021**, *9*, 40076–40085. [CrossRef]
61. Razmi, H.; Afshinfar, S. Neural network-based adaptive sliding mode control design for position and attitude control of a quadrotor UAV. *Aerosp. Sci. Technol.* **2019**, *91*, 12–27. [CrossRef]
62. Kun, D.W.; Hwang, I. Linear matrix inequality-based nonlinear adaptive robust control of quadrotor. *J. Guid. Control Dyn.* **2016**, *39*, 996–1008. [CrossRef]
63. Khatoon, S.; Gupta, D.; Das, L. PID & LQR control for a quadrotor: Modeling and simulation. In Proceedings of the 2014 International Conference on Advances in Computing, Communications and Informatics (ICACCI), Delhi, India, 24–27 September 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 796–802.
64. Joshi, G.; Virdi, J.; Chowdhary, G. Asynchronous deep model reference adaptive control. In Proceedings of the Conference on Robot Learning, PMLR, London, UK, 8–11 November 2021; pp. 984–1000.
65. Anderson, R.B.; Marshall, J.A.; L'Afflitto, A. Constrained robust model reference adaptive control of a tilt-rotor quadcopter pulling an unmodeled cart. *IEEE Trans. Aerosp. Electron. Syst.* **2020**, *57*, 39–54. [CrossRef]
66. Patnaik, K.; Zhang, W. Adaptive Attitude Control for Foldable Quadrotors. *IEEE Control Syst. Lett.* **2023**, *7*, 1291–1296. [CrossRef]
67. Dong, F.; Yuan, B.; Zhao, X.; Ding, Z.; Chen, S. Adaptive robust constraint-following control for morphing quadrotor UAV with uncertainty: A segmented modeling approach. *J. Frankl. Inst.* **2024**, *361*, 106678. [CrossRef]
68. Choi, S.Y.; Cha, D. Unmanned aerial vehicles using machine learning for autonomous flight; state-of-the-art. *Adv. Robot.* **2019**, *33*, 265–277. [CrossRef]

69. Yang, T.; Wu, H.N.; Wang, J.W. cc-DRL: A Convex Combined Deep Reinforcement Learning Flight Control Design for a Morphing Quadrotor. *arXiv* **2024**, arXiv:2408.13054.
70. Quan, L.; Han, L.; Zhou, B.; Shen, S.; Gao, F. Survey of UAV motion planning. *IET Cyber-Syst. Robot.* **2020**, *2*, 14–21. [CrossRef]
71. Sárosi, J.; Biro, I.; Nemeth, J.; Cveticanin, L. Dynamic modeling of a pneumatic muscle actuator with two-direction motion. *Mech. Mach. Theory* **2015**, *85*, 25–34. [CrossRef]
72. Bahl, S.; Nagar, H.; Singh, I.; Sehgal, S. Smart materials types, properties and applications: A review. *Mater. Today Proc.* **2020**, *28*, 1302–1306. [CrossRef]
73. Wang, X.; Zhao, J.; Pei, X.; Wang, T.; Hou, T.; Yang, X. Bioinspiration review of Aquatic Unmanned Aerial Vehicle (AquaUAV). *Biomim. Intell. Robot.* **2024**, *4*, 100154. [CrossRef]
74. Tanaka, S.; Asignacion, A.; Nakata, T.; Suzuki, S.; Liu, H. Review of biomimetic approaches for drones. *Drones* **2022**, *6*, 320. [CrossRef]
75. Shen, Y.; Chen, M.; Skelton, R.E. Markov data-based reference tracking control to tensegrity morphing airfoils. *Eng. Struct.* **2023**, *291*, 116430. [CrossRef]
76. Chen, M.; Liu, J.; Skelton, R.E. Design and control of tensegrity morphing airfoils. *Mech. Res. Commun.* **2020**, *103*, 103480. [CrossRef]
77. Chen, M.; Shen, Y.; Skelton, R.E. Model-Based and Markov Data-Based Linearized Tensegrity Dynamics and Analysis of Morphing Airfoils. In Proceedings of the AIAA SCITECH 2024 Forum, Orlando, FL, USA, 8–12 January 2024. [CrossRef]
78. Azar, A.T.; Koubaa, A.; Ali Mohamed, N.; Ibrahim, H.A.; Ibrahim, Z.F.; Kazim, M.; Ammar, A.; Benjdira, B.; Khamis, A.M.; Hameed, I.A.; et al. Drone deep reinforcement learning: A review. *Electronics* **2021**, *10*, 999. [CrossRef]
79. AlMahamid, F.; Grolinger, K. Autonomous unmanned aerial vehicle navigation using reinforcement learning: A systematic review. *Eng. Appl. Artif. Intell.* **2022**, *115*, 105321. [CrossRef]
80. Ye, X.; Song, F.; Zhang, Z.; Zeng, Q. A review of small UAV navigation system based on multi-source sensor fusion. *IEEE Sens. J.* **2023**, *23*, 18926–18948. [CrossRef]
81. Harun, M.H.; Abdullah, S.S.; Aras, M.S.M.; Bahar, M.B. Sensor fusion technology for unmanned autonomous vehicles (UAV): A review of methods and applications. In Proceedings of the 2022 IEEE 9th International Conference on Underwater System Technology: Theory and Applications (USYS), Kuala Lumpur, Malaysia, 5–6 December 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–8.
82. García, J.; Molina, J.M.; Trincado, J. Real evaluation for designing sensor fusion in UAV platforms. *Inf. Fusion* **2020**, *63*, 136–152. [CrossRef]
83. Kamel, M.; Verling, S.; Elkhatib, O.; Sprecher, C.; Wulkop, P.; Taylor, Z.; Siegwart, R.; Gilitschenski, I. The Voliro Omniorientational Hexacopter: An Agile and Maneuverable Tiltable-Rotor Aerial Vehicle. *IEEE Robot. Autom. Mag.* **2018**, *25*, 34–44. [CrossRef]