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A review of avian-inspired morphing for UAV flight control

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ABSTRACT

The impressive maneuverability demonstrated by birds has so far eluded comparably sized uncrewed aerial vehicles (UAVs). Modern studies have shown that birds' ability to change the shape of their wings and tail in flight, known as morphing, allows birds to actively control their longitudinal and lateral flight characteristics. These advances in our understanding of avian flight paired with advances in UAV manufacturing capabilities and applications has, in part, led to a growing field of researchers studying and developing avian-inspired morphing aircraft. Because avian-inspired morphing bridges at least two distinct fields (biology and engineering), it becomes challenging to compare and contrast the current state of knowledge. Here, we have compiled and reviewed the literature on flight control and stability of avian-inspired morphing UAVs and birds to incorporate both an engineering and a biological perspective. We focused our survey on the longitudinal and lateral control provided by wing morphing (sweep, dihedral, twist, and camber) and tail morphing (incidence, spread, and rotation). In this work, we discussed each degree of freedom individually while highlighting some potential implications of coupled morphing designs. Our survey revealed that wing morphing can be used to tailor lift distributions through morphing mechanisms such as sweep, twist, and camber, and produce lateral control through asymmetric morphing mechanisms. Tail morphing contributes to pitching moment generation through tail spread and incidence, with tail rotation allowing for lateral moment control. The coupled effects of wing–tail morphing represent an emerging area of study that shows promise in maximizing the control of its morphing components. By contrasting the existing studies, we identified multiple novel avian flight control methodologies that engineering studies could validate and incorporate to enhance maneuverability. In addition, we discussed specific situations where avian-inspired UAVs can provide new insights to researchers studying bird flight. Collectively, our results serve a dual purpose: to provide testable hypotheses of flight control mechanisms that birds may use in flight as well as to support the design of highly maneuverable and multi-functional UAV designs.

1. Introduction

For over a century, aeronautical engineers have drawn inspiration for aircraft control and design from birds. The Wright brothers, credited with the first powered and controlled aircraft flight, developed a roll-control mechanism inspired by observations of bird flight [1]. However, to this day, birds demonstrate flight that is often more maneuverable than comparatively-sized aircraft [2] such as navigating through crowded cities and forests [3] as well as performing evasive maneuvers to escape from predators [4]. Birds are able to achieve this impressive control despite flying within the atmospheric boundary layer, which presents unique control challenges due to the large absolute variation in wind speeds and direction compared to large-scale aircraft [5–7]. These flight capabilities are, in part, permitted by neurological control [8,9] combined with birds' physical capability to dynamically morph their wing or tail shape [10,11]. Together, these capabilities have galvanized a new generation of avian-inspired morphing uncrewed aerial vehicles (UAVs), often with the goal of harnessing avian flight control to enable multi-objective tasks and missions [12]. However, currently it is difficult to identify which aspects of avian flight will provide the desired control enhancements as there is a lack of compiled information on the advantages and disadvantages provided by avian-inspired morphing flight control. To fill this gap, we compiled and reviewed existing

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studies on birds and bird-scale UAVs to discuss the varied methods of control that may be gained from avian-inspired morphing.

There are many challenges that must be overcome to develop a comprehensive understanding of avian aerodynamic control. For example, although modern technology is enabling more advanced quantitative measurements (discussed in the following sections), many avian flight control studies rely on in-flight tracking of birds and their associated morphology to estimate the function of different morphing behaviors [9]. These techniques, although necessary and informative, will introduce experimental uncertainty and can only evaluate the observed maneuvers [13]. Additionally, avian behavior and movements are often variable and/or inconsistent when measured on an individual bird, between different birds, and between different bird species [14,15]. This variability complicates the task of directly linking flight mechanics to observations of live flying birds. To address these difficulties, advances in engineering capabilities and analytical, experimental, and/or computational models can be leveraged to quantitatively determine the control forces and moments associated with specific maneuvers for avian-scale UAVs and reconstructed bird geometries.

Within these challenges lies a valuable opportunity as there are over 10,000 species of birds [16] and each species may offer unique insights into effective future UAV designs [13]. However, birds are not necessarily optimized for any specific form of flight or locomotion [17]. Therefore, to quantify and test whether avian-inspired control could supplement or supersede existing UAV control mechanisms, engineering techniques can be used to support biological understanding.

Even if avian-inspired morphing shows promise for a specific application, there are additional difficulties associated with incorporating any beneficial avian-inspired control mechanism into a morphing UAV [12]. Replicating a biological system is non-trivial and it is possible that an avian-inspired UAV design that recreates the desired morphing shapes may reduce or negate any control or performance enhancements solely due to additional mechanism weight, loss of structural rigidity, or increased design complexity [12]. These multi-disciplinary challenges must be evaluated when considering the effectiveness of avian-inspired designs.

When applying an engineering framework to biological systems it becomes advantageous to implement a three-pronged approach, which incorporates analytical, computational, and experimental methods. Each of these methods has advantages and drawbacks. For example, analytic methods provide substantial insight into relationships between design parameters and performance, and can be used to evaluate and compare results over a wide range of design parameters. However, these methods can suffer from assumptions or approximations about the flow regime or geometry that must be made in order to obtain a closed-form or tractable solution. Computational methods often include better approximations for the flow physics over a range of flow conditions, but are generally limited in the range of cases that can be studied due to high computational costs. Finally, experimental methods are valuable as they allow the study of actual birds and UAVs in flight. However, these methods suffer from inaccuracies due to measurement uncertainty, instrumentation, and experimental setup. For example, to obtain measurements of motion or flow, birds or aircraft are usually placed in an unnatural environment (such as a wind tunnel) or condition that can alter their flight and give results that do not match their true flight behavior.

Leveraging all three methodologies is especially critical because, unlike traditional aircraft, birds and small-scale UAVs fly in intermediate Reynolds numbers, where the flow is prone to transitioning between laminar and turbulent regimes [13,18]. In addition, birds' wing and tail shapes often differ substantially from rectangular, planar wings. The aphorism suggested by George Box applies to our present challenge of correctly understanding the flow and flight physics of bio-inspired flight, "All models are wrong, but some are useful''.

In this review, we gathered much of the foundational work and placed it in context to other similar work. To make progress in this complex field, it is imperative to understand the limitations of each study. As stated above, analytic work is often limited to certain flow regimes, while computational and experimental studies are often limited in scope due to specific species, experimental setup, or flight conditions. For the sake of brevity, we did not provide a detailed discussion of all the limitations in every study, although as applicable we highlighted any situation where there were contrasting results or unexpected conclusions. In all, our review highlights that there is more work needed to advance the field towards a complete understanding of avian morphing flight control.

Here, we aimed to address these challenges and bridge the fields of avian biology and aerospace engineering through a comprehensive analysis of the current literature on active wing and tail morphing (Fig. 1) including both biological bird studies and avian-inspired UAVs. By compiling and contrasting the results from these two complementary fields, we identified current challenges and opportunities for future cross-disciplinary collaboration and communication. This review is intended to serve as a dual-purpose resource: (1) for aerospace engineers to gain an understanding of avian flight control in hopes of advancing the design of multi-functional and adaptive UAVs and, (2) for biologists to gain an understanding of avian-inspired UAV flight control in hopes of providing testable hypotheses for how similar controls may be used by live birds.

In this work, flight control refers to a flyer's ability to adjust its aerodynamic forces and moments to purposefully manipulate the velocity vector or to adjust its stability characteristics. To focus our discussion on flight control, we differentiated control from performance enhancements. Performance enhancements are another important application of avian-inspired UAV designs serving to minimize drag and/or maximize efficiency in steady flight [12,19]. Because performance and control characteristics are not always easily decoupled, we included references to the performance enhancing effects of morphing throughout this review. To provide structure to the discussion, we divided sections into longitudinal (i.e., changes in lift, drag and pitching moment) and lateral (i.e., changes in side force, roll and yaw) effects. However, during fast maneuvers and asymmetric flight conditions, it is likely that these modes are coupled. Additionally, we evaluated a flyer's static stability characteristics, which define the tendency to return to an initial position after a disturbance. Note that a discussion of full flight stability requires an understanding of dynamic stability. Dynamic stability is discussed briefly in some sections but, there is currently relatively little published work on avian-inspired morphing dynamic stability.

To streamline our discussion, we defined a few topics to be outside the scope of this review. First, we limited our discussion to gliding flight only and refer readers to previous reviews pertaining to flapping flight [2,20,21]. Next, we focused on the avian-specific Reynolds number regime (approximately 1.5×10^4 to 5.2×10^5 [13]) unless otherwise stated, because avian morphing configurations and behaviors are more readily comparable to similar-sized UAVs that fly in similar flow regimes. We direct the reader to existing reviews for details on large-scale morphing aircraft [12,19,22]. Further, we did not include variable-span UAV designs because, although birds do have the ability to retract and extend their wings, this is accomplished by manipulating the elbow and wrist joints, which causes changes in wing sweep and dihedral. Thus, any area/span changes are accounted for within those designs and are discussed in Sections 2.2 and 2.3. Refer to studies by Beaverstock et al. [23,24] for information on flight control capabilities of variable span UAVs. Next, we did not delve into the complex study of the avian neurological system or any mechanosensor systems which should eventually be included in this discussion. We refer readers to Altshuler and Srinivasan [8] and Altshuler et al. [9] for further details. Finally, although bird wings are flexible, we limited our discussion of aeroelastic effects within this review as there are few studies on both birds and avian-inspired UAVs that have discussed or quantified the contribution of actuator flexibility to aerodynamic

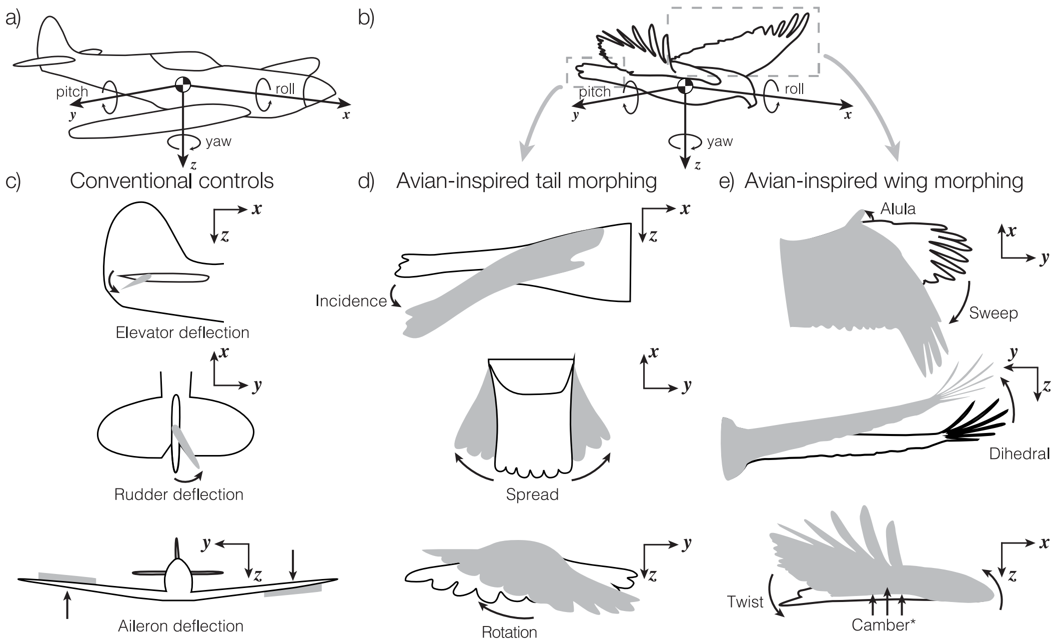

Fig. 1. Active flight controls for (a) aircraft and (b) birds are investigated. The degrees of freedom in (c) conventional aircraft control differ substantially from those in the avian (d) tail and (e) wings.

control in gliding flight. It will be important for future studies to quantify and evaluate the role of flexibility in flight control. We included a brief discussion of aeroelastic effects on camber morphing in Section 2.6 due to its instrumental historical context within the field. For comprehensive reviews of aeroelasticity in flapping flight and aircraft design, please refer to Ajaj et al. [25] and Shyy et al. [21].

In all, we compared and contrasted the flight control implemented in non-flapping, non-rotary, avian-inspired UAVs and gliding birds that is permitted through wing (Section 2) and tail (Section 3) morphing. To accomplish this goal, we independently investigated the effects of each major morphing degree of freedom informed by existing biological research and engineering studies. With respect to wing morphing, we focused on the control gained from variable wing sweep (Section 2.2), dihedral (Section 2.3), twist (Section 2.4), camber (Section 2.6), and the alula (a thumb-like digit, Section 2.5) (Fig. 1e). We also independently investigated the control gained from tail incidence (Section 3.2), spread (Section 3.3), and rotation (Section 3.5) (Fig. 1d). Finally, we compiled existing work on the coupled effects of wing and tail morphing (Section 4), although this information is relatively limited. As the field progresses, it will become necessary to re-evaluate avian-inspired control with coupled morphing parameters to quantify the benefits of avian wing morphing for UAV designs.

Note that the coupling influence of wing geometry, tail geometry, wing incidence, tail incidence, and locations of the main wing and tail relative to the center of gravity on longitudinal pitch stability, control, and maneuverability has been studied on traditional aircraft for some time [1,26–30]. A solid understanding of these relationships, their development, and limitations is helpful for accurately assessing and understanding work on avian-inspired flight including coupled wing and tail morphing and thus we recommend readers to explore these traditional references throughout the paper for further details. Appendix A includes a glossary intended to establish a common framework between the biological and engineering terms used within this survey. Within this work, we largely discuss our understanding of avian control and stability through the lens of specific case studies supplemented by theoretical expectations.

2. Wing morphing

Bird wings can morph both passively and actively to adjust aerodynamic forces and moments in flight. We primarily investigated wing morphing inspired by the degrees of freedom that birds are known to actively control (Fig. 2) including variable wing sweep (Section 2.2), dihedral (Section 2.3), twist (Section 2.4) and one of the forelimb digits known as the alula (Section 2.5). In addition, we also discussed UAVs that employ active camber-morphing systems (Section 2.6), as a substantial body of work has focused on designs inspired by the smooth change in camber observed in birds. The effects of passive feather flexibility on camber morphing are briefly discussed, but the coupled role of passive and active deformations necessitate further research to develop a complete understanding of avian flight control.

Active wing morphing in birds is realized by actuating the skeletal joints, predominately the shoulder, elbow, wrist, and digits [9,31–33]. A bird's wing joints are homologous to other tetrapod (four-limbed animal) forearms including the human arm [34]. However, unlike our arms, the range of motion of a bird's elbow and wrist is often constrained at higher extension angles [31,32]. This constriction was historically explained as being a result of a planar four-bar linkage system (parallelogram or "drawing parallels") [35]. However, a recent study on pigeons (*Columba livia*) identified that two additional linkages were required to properly replicate the observed out-of-plane effects of wing morphing, resulting in a non-planar six-bar linkage [36]. Under this improved linkage model, the coupled motion of the elbow and wrist are prescribed while the digit and shoulder joints operate independently from the rest of the linkage.

Within the available range of motion, birds can use muscular control to actuate their skeleton and realize a wide range of distinct, and often non-planar, wing shapes in flight [31,32]. The simplification of modeling the wing as a six-bar linkage does not capture that the elbow and wrist joints do have some capacity for rotation about three degrees of freedom: extension/flexion, pronation/supination (twist) and elevation/depression [32], although each joint's range of motion varies based on the species [9,32,37]. Although the majority of wing shape change is accomplished by actuating the elbow and wrist [31], one of the digits (digit II [38], hereafter called the "finger") is capable of independent rotation. This digit's range of motion has been quantified to be 30° in a study on pigeons [36] and to average 58° for non-diving flyers [37]. Another digit (digit I [38]), known as the alula, has been well-studied but its range of motion has not yet been quantified. Collectively, the unique wing shapes that are available to birds throughout their range of motion have inspired a multitude of morphing wing designs throughout the history of aviation.

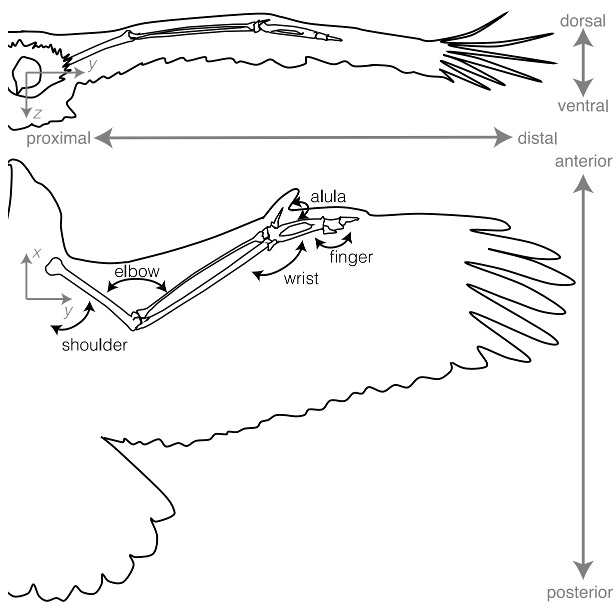

Fig. 2. Definition of the key wing morphing parameters used in the following sections. Simplified view of a bird's wing highlighting the skeletal structure which can be actively controlled by activating the wing muscles. The skeletal drawing is adapted from [32]. For details on camber-morphing parameters refer to Fig. 6.

2.1. Wing morphing mechanisms

Avian-inspired morphing wing designs often implement controllable mechanical joints inspired by skeletal joints (Figs. 3 and 4). In this work, a "shoulder-inspired" joint refers to a mechanical joint that is directly located at the junction between the wing and the body. An "elbow-inspired" joint refers to a joint located at a mid-span position, usually aft of the shoulder joint, from which the wing is predominately swept forward relative to the position of the joint on the y-axis (Fig. 2). A "wrist-inspired" joint refers to a joint located at a more distal spanwise location than the elbow, which predominately affects the distal portion of the wing. Finally, we separated the two major digits into two groups. First, "finger-inspired" joints refer to a second, wrist-like mechanism placed even more distally along the wingspan than the wrist. Second, "alula-inspired" joints refer to an additional, smaller control surface attached at a mid-span location to the wing's leading-edge For each degree of freedom, we summarized published results on the effects of both symmetric and asymmetric wing morphing to extract the implications for longitudinal and lateral control, respectively.

All avian wing joints can be implemented with variable sweep, dihedral, and twist; however, most UAV designs tend to select one degree of freedom per joint [39]. This is likely due to the inherent challenges of implementing a multi-degree of freedom joint. Note that, unlike avian-inspired morphing, the avian wing musculoskeletal system leads to non-linear, coupled changes to the spanwise sweep, dihedral, twist and overall planform shape simultaneously (as demonstrated in Figs. 3 and 4). Realizing biologically accurate wing shapes on a UAV is a substantial challenge because the aerodynamic benefits gained from wing morphing must be substantial enough to justify any design modifications.

There are a variety of methodologies that could be used to recreate avian wing shape changes within a UAV. A large obstacle to overcome when implementing any of these morphing designs is proper reinforcement of the mid-span joints to account for the aerodynamic loads, without substantial weight addition. Further, many of these morphing shapes require large-scale wing deformation which, in turn, requires new materials or multi-structure designs to be able to maintain enough rigidity to form an effective lifting surface.

Some possible structural solutions include the use of feather-like structures on UAVs (discussed in the following section) or flexible membranes. The study of flexible-membrane wings is a promising and ongoing field of research [21], often inspired by bats or insects. These solutions are supported by advances in smart materials and manufacturing techniques that provide novel methods to design and manufacture flexible membrane morphing wings [12]. Currently, most UAV morphing wing designs remain at a preliminary stage of technological readiness with a focus on investigating whether specific morphing degrees of freedom provide enough benefits to warrant the increased complexity and, in some cases, increased weight. Further details on these specific morphing-wing designs and manufacturing challenges have been discussed in previous reviews including Barbarino et al. [12], Vasista et al. [19], and Li et al. [40]. Readers are referred to the work by Gomez-Tamm et al. [41] for a detailed review of bio-inspired actuators.

2.2. Wing sweep

Active wing sweep morphing is not a new technology, and over the decades, many aircraft have been designed with sweep-morphing wings. There has been a particular focus on supersonic fighter aircraft [12]. A variable sweep angle allows supersonic aircraft to compromise between efficient low speed flight and improved drag and handling characteristics in cruising or maneuvering flight [12]. However, these designs drew, at most, minimal inspiration from avian flight because birds glide well below the speed of sound ($0.01 <$ Mach number < 0.08 [13]).

Nonetheless, wing sweep morphing has been implemented successfully on many UAVs [42,43]. Grant et al. [44] designed one of the first bird-scale UAVs that implemented joint-inspired wing sweep morphing in flight. Inspired by gull flight, this UAV had wrist-inspired and shoulder-inspired joints that were constrained to a single horizontal plane and allowed a wide variety of possible wing shapes (Fig. 3) [44]. Many UAVs have since been designed with wing-sweep mechanisms including those by Wright [45] with shoulder-inspired joints, Di Luca et al. [46] with wrist-inspired joints and Ma et al. [47] with both shoulder-inspired and elbow-inspired joints. Recently, the PigeonBot by Chang et al. [33] and the Lishawk by Ajanic et al. [48] were directly inspired by the pigeon and northern goshawk respectively. Both designs used wrist-inspired joints, and Chang et al. [33] further implemented a finger-inspired joint.

Shoulder-inspired sweep morphing permits a solid body rotation of the wing about the wing root, whereas wrist-inspired sweep morphing requires that the trailing-edge of a wing folds onto itself while maintaining a functional lifting surface. This often results in an "M-shaped" wing configuration [49] when looking at the flyer from the ventral or dorsal view (Fig. 2). From a structural perspective, the large wing area change due to a wrist joint is often achieved by using thin overlapping structures [46,48,50,51] or, in the case of birds and the PigeonBot, real feathers [33]. However, implementing this multi-structure approach in engineered designs often causes staircase-like wing dihedral in the folded wing shape, which Hui et al. [50] found to increase the static roll stability compared to a continuous wing. Regardless, wing sweep itself affects both longitudinal and lateral flight characteristics.

2.2.1. Longitudinal

Symmetric, backwards wing sweep on bird-scale flyers reduces the lift slope and decreases the drag production at high angles of attack [10, 30,42,48,50–52]. Ajanic et al. [48] showed that forward swept wings could be used at low speeds to increase lift generation and provide weight support, whereas backwards swept wings could be used at high speeds to reduce power requirements, similar to large-scale aircraft and studies on swift wings [10]. Likewise, Hui et al. [50] found that an

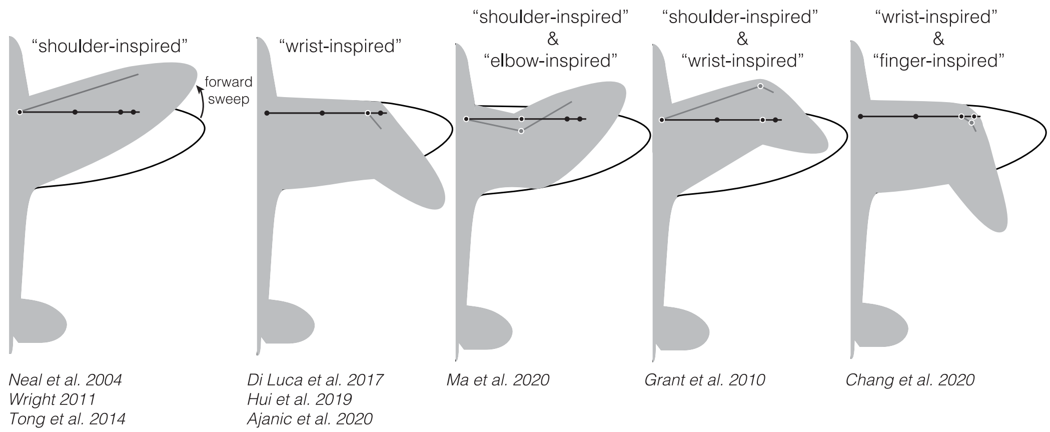

Fig. 3. Simplified renditions of the different UAV implementations of avian-inspired wing sweep morphing. Note that the wing or fuselage shapes are not necessarily representative of the individual UAV designs.

extended, wrist-inspired joint was more efficient (i.e., produced a larger lift-to-drag ratio) at lower Reynolds numbers (0.93×10^5) while the folded wing was more efficient at higher Reynolds numbers (1.87×10^5).

As both UAVs operate on the same scale as birds, it is likely that these conclusions extend to live birds. Indeed, many wind tunnel studies of live gliding birds have shown that birds will fold their wrists as wind speeds increase, which has been suggested to allow birds to achieve a higher aerodynamic efficiency across a range of flight speeds, similar to the above UAV results and theoretical expectations [13,53–58]. The outcomes of these biological and engineering studies highlight the importance of studies across various Reynolds number regimes, especially because different bird species fly in substantially different flight regimes [13].

In conjunction with these performance enhancements, wing sweep morphing can also be used as a method of longitudinal control. A commonly observed avian wing sweeping response is associated with initiating a pitch up motion. For example, the steppe eagle (*Aquila nipalensis*) begins a perching maneuver by sweeping its wings forward at the shoulder and aft at the wrist [14,59]. Two separate UAV flight tests showed that sweeping the wing forward provided a strong pitch-up response and, if combined with increased tail spread, could be used to rapidly attain high angles of attack similar to that observed during avian perching maneuvers [45,48,60].

Interestingly, there is evidence that when a bird's body is physically pitched downwards in the absence of airflow, the bird will respond by sweeping its wings forward [61]. This morphing behavior, combined with the UAV results, suggests this response could effectively provide an immediate positive pitching moment in response to a downwards pitch perturbation during flight. Brown [61] suggested that this wing morphing response provides evidence that birds use active control to ensure a level flight path. Similarly for UAVs, wing sweep may be a useful active control methodology to maintain a level flight path in response to pitching perturbations.

It is well-established that longitudinal stability characteristics will also be affected by wing sweep morphing [29]. When a wing is swept backwards symmetrically, both the wing's aerodynamic center and the center of gravity of the UAV will shift backwards (Fig. 2) [48,62]. This backwards shift can be enhanced by adding a second morphing joint, such as a shoulder, to increase the effective wing sweep angle [44]. Ajanic et al. [48] and Neal et al. [62] found experimentally that wing sweep morphing caused a substantially smaller shift in the center of gravity compared to the shift in the aerodynamic center on their aircraft configurations. This carries over to birds as a recent study has shown that wing morphing across the complete range of motion of a bird has a only minor effect on shifting the center of gravity [63]. As a result, wing sweep morphing permits a variable static margin, where a backwards swept wing is associated with an increased static margin (increased longitudinal stability) and a forward swept wing reduces the static margin (reduced longitudinal stability).

To this end, Ajanic et al. [48] confirmed that wing sweep alone could effectively control the static margin and therefore the longitudinal static stability throughout flight. The results from the Lishawk agree with Neal et al. [62]'s previous wind tunnel study on a variable-sweep wing design. However, the variable static margin offered by these designs can cause undesirable handling qualities for human pilots because pitch control effectiveness gained through a traditional elevator directly depends on the longitudinal static stability characteristics [28,29]. Therefore, wing sweep morphing leads to a variable control effectiveness and necessitates a controller that adjusts the control forces accordingly.

The correlation between wrist-inspired sweep and longitudinal stability was linked to avian wing geometries by a study of rigid gull wings, which additionally found that folding the elbow in tandem with the wrist resulted in the most statically stable configuration [39]. In addition, a recent comparative study of avian inertia estimated that by morphing only the elbow and the wrist, 17 of 22 investigated bird species had the ability to shift between stable and unstable flight [63]. Further, the associated evolutionary analysis revealed evidence of selective pressures acting to maintain birds' ability to shift between these stability modes. This outcome coupled with Ajanic et al. [48]'s Lishawk design suggest that this may be a key feature to effectively incorporate true avian-like maneuverability in future UAV designs. Note that morphing the elbow and wrist together leads to changes in the sweep, dihedral and twist in a way that is not easily decoupled.

Many bird species fold their wrists (resulting in backward sweep of their wings) and reduce their wingspan as wind speeds increase [53–58,64–67], which possibly suggests that birds will have increased longitudinal static stability when flying at higher speeds. Alternatively, or in conjunction with the increase in stability, this folding behavior at high speeds may also reduce structural wing loading and/or increase flight efficiency, as discussed previously [48,50]. Note that the wing area reduction due to wrist folding in bird wings does not guarantee lift reduction. Harvey et al. [39] found that folded wrist configurations in biologically accurate morphing gull wings were not directly associated to reduced lift due to increased tip wash-in (i.e., wing tips at a higher angle of attack than the wing root), which effectively increased the lift over a portion of the wing [39].

Finally, differences in control methodologies may exist between diving and gliding flights. A computational study of modeled peregrine falcons (*Falco peregrinus*) in a diving configuration (wings nearly fully folded into a "cupped" position) estimated that these birds would be marginally unstable in the longitudinal axis, which is hypothesized to be useful for high speed maneuvering [68]. Note that the model's center of gravity may not be at the exact location of a live bird's center of gravity and thus all stability discussions necessitate further information on the inertial characteristics of a live bird.

This study also showed that increasing the wrist sweep near the end of a pitch-up portion of a dive led to a configuration that matched delta wing theory [68]. Further research is required to better understand the physical implications of this stooping behavior and to confirm if a bird's high-speed stability differs between gliding and diving flight. This will in turn provide insights into beneficial control methodologies for comparable UAVs who wish to both successfully glide and dive.

2.2.2. Lateral

Birds also can manipulate their wing joints asymmetrically [69], which generates asymmetric forces that can be used for lateral control [68]. For example, Durston et al. [70] observed a peregrine falcon entering a roll with asymmetric wing sweep, while Gillies et al. [14] observed a steppe eagle asymmetrically morphing its wings while simultaneously adjusting the wing's angle of incidence during a roll-over and other unsteady maneuvers. Likewise, Oehme [71] documented a hen harrier (*Circus cyaneus*) adjusting its wing incidence angles while also folding its right wing at the wrist, which lead to the bird rolling to the right.

In traditional aircraft, ailerons are the main form of lateral control on the wings (Fig. 1). Aileron deflection creates asymmetric lift and drag on the wings which induces a rolling and yawing moment. However, ailerons can suffer from control reversal, a phenomenon where the flight controls generate an opposite moment than commanded. Although this is commonly due to aeroelastic effects at increased dynamic pressures (high flight speeds) [26], it can also be caused by flying at high angles of attack which can generate substantial adverse yaw and lead to roll reversal [29]. As birds regularly fly at high angles of attack and have flexible wings [14,72], their flight control mechanisms may offer inspiration about how to negotiate these complex aerodynamic effects.

Current evidence from multiple morphing-wing UAVs suggests that variable, asymmetric sweep angles, implemented with either shoulder-inspired and wrist-inspired joints, can provide an effective alternative to ailerons for roll control [33,46,50,73]. Ajanic et al. [48] showed that allowing one wing to sweep forward and the other backward on a wrist-inspired design provided effective roll moment control even past stall. Sweeping a single wing backwards has also been shown to allow for smaller turn radii and thus more lateral maneuverability [74]. Note that wind tunnel tests on prepared swift wings found that even symmetric backwards wing sweep would reduce the turn radius, but also that the turning rate would be reduced [10].

Simulations by Ma et al. [47] found that a flexible trailing-edge would have higher roll control authority than asymmetric elbow-inspired joint morphing because asymmetric trailing-edge deflection generated a larger rolling moment for the same lift coefficient without a shift in the static margin (refer to Section 2.6 for details on trailing-edge devices). Therefore, even though avian-inspired, controllable asymmetric wing sweep may provide an alternative roll-control device that does not suffer from reversal at high angles of attack, these advantages might not supersede those provided by other control mechanisms.

Grant et al. [74] suggested that asymmetric wing sweep could be used to allow improved sensor pointing in the face of crosswinds and gusts. Since sensor pointing allows a consistent heading for the fuselage, flying birds that are targeting a specific location might be able to use a similar approach. Interestingly, an analysis of migrating bee-eaters found that the presence of crosswinds had no effect on their flight speed nor on the style of flight being used (flapping, soaring-gliding or mixed) [75]. Therefore, the authors suggested that these birds likely had another method to compensate for lateral drift due to the encountered crosswinds. It is possible that this compensation could be provided by asymmetric wing morphing or tail morphing. An alternative explanation may be provided by considering that birds use their neck to stabilize their head independent from their body [69,76]. This additional degree of freedom decouples body and head motion and likely reduces the importance of body orientation for birds compared to UAVs.

Lateral control using asymmetric wing sweep would require substantially different control algorithms than conventional aircraft. Unlike ailerons, asymmetric wing sweep results in a linear relationship between the generated lift and rolling moment such that increasing the lift will increase the rolling moment [46]. This relationship between rolling moment and lift for asymmetric sweep morphing can be predicted from aeronautical theory because a swept wing has a lower lift slope than an unswept wing, as discussed previously [30]. Thus, for a given increase in angle of attack (increasing the lift), the unswept wing will develop a larger change in the lift force than the swept wing. This will further enhance the lift asymmetry and thus contribute to an increased rolling moment as the lift increases.

Furthermore, while traditional ailerons control roll by specifying a fixed roll rate, Chang et al. [33] found that wrist-inspired and finger-inspired sweep morphing instead appeared to specify a fixed roll angle. This conclusion was reached after outdoor flight tests of the UAV at a given wing sweep configuration showed a plateauing time response of the roll angle while the roll rate remained highly variable. However, note that this result contradicts with results from Di Luca et al. [46] who found that wrist-inspired wing sweep morphing led to a constant roll rate in time similar to traditional aircraft. Further investigation is required to further investigate the association between the sweep morphing and the roll angle.

Finally, varying the wing sweep will also affect the lateral static stability of a flyer. Theory predicts that sweeping the wing backwards should increase both the static roll and yaw stability [29]. The theoretically expected stability trend with sweep was confirmed for bird-scale UAVs by multiple independent experimental and numerical studies, which found that both symmetric wrist-inspired or shoulder-inspired sweep increased static roll stability [50,77] and static yaw stability [44,50]. Note that prediction of static lateral stability is notoriously complex due to the interference effects between different wing, fuselage, and tail components [78].

An analytical analysis has proposed that, due to their small size and inertia, the sweep of a bird's wing provides sufficient lateral stability (both statically and dynamically) to replace a vertical tail [79]. Similarly, a swept-wing configuration is often incorporated into rudderless flying wing aircraft as a method to achieve lateral stability in the absence of a vertical stabilizer [80].

Note that asymmetric wing sweep had a negligible effect on the static roll stability [50], which supports the use of sweep as an effective method of roll control independent of roll stability. However, Grant et al. [44]'s results showed that asymmetric sweep produced the same yaw stabilizing effect as symmetric sweep but with a lower magnitude. Therefore, asymmetric wing sweeping for lateral control will inherently affect the static yaw stability of a flyer and may face the same control issues mentioned when discussing the longitudinal effects.

2.3. Wing dihedral

Another degree-of-freedom that can be controlled by avian-inspired wing morphing is the dihedral angle (Fig. 4). Birds can readily adjust this parameter by elevating/depressing the wing at the shoulder joint [81], at each joint within the wing [32], or by extending the elbow [31], the latter being a result of the non-planar linkage system. There exists a wide range of dihedral angles used by different birds and species. For example, raptors can use large shoulder dihedral angles while in soaring flight [69] or anhedral angles in slow gliding flight [81]. In contrast, gulls are often observed gliding with a characteristic positive dihedral angle at their shoulder and a negative dihedral angle (anhedral) at a midspan position (Fig. 4) [31]. A bird's capability to elevate/depress their wrist joints varies between species and tends

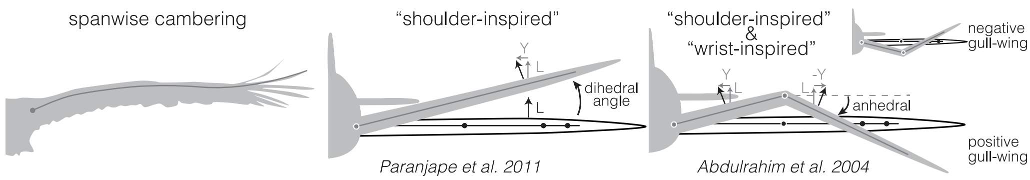

Fig. 4. Simplified renditions of the different UAV implementations of avian-inspired wing dihedral morphing. The shoulder-inspired configuration results in consistent adjustment to the lift (L) and side force (Y) while the gull-wing inspired morphing leads to side forces that counteract each other.

to be measurably reduced when flying with a more extended wing configuration [32].

Besides dihedral changes due to the shoulder, birds tend to morph their dihedral using a continuous curvature along the span known as spanwise cambering (Fig. 4). Spanwise cambering inspired by a gull-wing enhanced the aerodynamic efficiency of a rigid wing [82]; however, once constructed to morph between a planar and cambered shape, the design did not realize the expected benefits [83]. Harvey et al. [31] studied real gull wings in a wind tunnel and found that by increasing the spanwise cambering of the wings, gulls may be able to reduce their longitudinal static stability. Aside from this work, there is little information on how continuous spanwise camber morphing may contribute to flight control. This is likely due to the increased complexity of constructing and actuating a non-planar structure. Thus, in this review we discussed solely discrete linear changes in the dihedral angle along the wingspan as shown in Fig. 4.

Some of the first bio-inspired, dihedral-morphing UAVs include designs by Abdulrahim and Lind [84] and Paranjape et al. [85]. Paranjape et al. [85] investigated the potential control offered by a shoulder-inspired joint on tailless UAVs [85–87] where two of these UAVs could also adjust the wing twist [85,87]. Abdulrahim and Lind [84] designed a gull-inspired aircraft (WhoopingMAV [88]) that was able to morph using both a shoulder-inspired joint and a wrist-inspired joint. In this review, the classical gull-wing shape is defined as a positive gull-wing configuration whereas anhedral at the shoulder joint and dihedral at the wrist joint is a negative gull-wing configuration (Fig. 4). Note that birds are likely unable to achieve a large degree of negative gull-wing configuration due to their musculoskeletal linkage system.

2.3.1. Longitudinal

Increasing the dihedral angle at the shoulder joint reduces the lift slope and affects drag production [89]. Note that while the effect of dihedral on drag is expected to be relatively minor for smaller dihedral angles [85,89], CFD simulations by Sachs and Moelyadi [90] found a substantial drag reduction at larger dihedral angles (≈45°). Paranjape et al. [85] used flight testing and analytical modeling to show that variable dihedral (up to 60° on either wing) of a shoulder-inspired joint allowed control of both the flight speed and the flight path angle. Although this work did not compare dihedral effectiveness to that obtained from a conventional elevator, this result suggests that dihedral control alone may be an effective method to control the longitudinal orientation of a UAV.

Durston et al. [70] found that a barn owl (*Tyto alba*) glided with a positive wing camber and anhedral angle on the wings which led them to suggest that these two elements provided evidence for a negative zero-lift pitching moment as would be expected theoretically. This result, in combination with the observation that the owl's flight path was relatively steady led the authors to suggest that the owl was flying in an unstable configuration. As highlighted by Durston et al. [70] further analytical and numerical work is required to verify this experimental work for the barn owl's configuration and to determine how variation in anhedral angle may be used to control longitudinal stability in birds.

Gull-Wing Configuration

Preliminary flight tests and dynamic modeling by Abdulrahim and Lind [84] found that both positive and negative gull-wing configurations decreased the glide ratio and climb rate when compared to the planar design. Flight testing found that the positive gull-wing configuration had more favorable stall characteristics than the negative configuration, especially at low speeds, as the negative configuration experienced aggressive stalls [88]. Abdulrahim and Lind [84] also quantified the effects of morphing on the frequency and damping ratios of the longitudinal dynamic stability modes. When compared to the planar wing configuration, the gull-wing UAV reportedly responded slower to elevator inputs. Despite these advances, there is little existing information on how, or if, gull-wing morphing itself provides an effective form of longitudinal control.

Birds have been observed to use wing dihedral changes as a method for active flight control. Harvey et al. [31] found that gulls use spanwise cambered configurations significantly more often in windier and gustier conditions and proposed that adjusting the spanwise camber provides a method to actively respond to gusts. Reynolds et al. [7] found that a gliding steppe eagle would "tuck" its wings (i.e., transiently using a large shoulder anhedral angle) in response to atmospheric turbulence. In contrast, Cheney et al. [91] observed that a barn owl increased its wing shoulder dihedral in response to vertical gusts which, in part, enabled the bird to minimize vertical accelerations and maintain stable body positioning. More work is required to confirm if such methodologies would be effective on a UAV, but these biological results suggest that gust alleviation could be an additional benefit to using avian-inspired dihedral morphing wings.

2.3.2. Lateral

Adjusting the wing dihedral angle affects the resultant side force vector and, when morphed asymmetrically, will result in asymmetries in the generated side force which can be manipulated to achieve lateral control [90]. Paranjape et al. [85] analytically showed that asymmetric shoulder dihedral could control yaw more effectively than a rudder when at high angles of attack, depending on the distance between the center of gravity and the tail aerodynamic center.

Similarly, it is likely that increasing the distance between the wing's aerodynamic center and the center of gravity will increase the lateral control effectiveness of the wing dihedral. For an aircraft with dihedral morphing control, Paranjape et al. [85] found that placing of the center of gravity either in front of or behind the wing's aerodynamic center yielded a trade-off between lateral and longitudinal control.

In a later study, Paranjape et al. [87] showed that asymmetric dihedral control could produce changes in sideslip and permit coordinated turns. The maximum turn rate was achieved by combining dihedral morphing with asymmetric wing twisting. However, this UAV revealed that the yaw control effectiveness of dihedral morphing switched signs between low lift and high lift conditions [85]. This control reversal would present substantial controllability challenges. Later work identified that incorporating trailing-edge flaps as a supplemental control successfully ensured that yaw control effectiveness remained the same sign across a broad range of angles of attack [86,92]. Therefore, it is possible that birds may also experience dihedral control reversal between low- and high-lift conditions, although further research will be required to confirm this hypothesis. Even if this is the case, the additional degrees of freedom available to birds may be used to mitigate these effects.

Shoulder-inspired, symmetric dihedral angle adjustments will affect the static lateral stability of a flyer. In general, positive dihedral increases roll stability and negative dihedral (anhedral) decreases roll stability [29,78]. Additionally, in most cases, a vertical component of a wing increases yaw stability if it is behind the center of gravity, and decreases yaw stability if it is in front of the center of gravity [93]. Interestingly, numerical simulations of a symmetric pigeon wing configuration found that similar to the control reversal previously discussed, the sign of the static yaw and roll stability had a non-linear relationship with the dihedral angle [90]. Consistent with theory, when the dihedral angle was increased from 0° to 22.5°, the roll stability increased in conjunction with a reduction in yaw stability. However, further increasing the dihedral from 22.5° to 45° had the opposite effect, yielding decreased roll stability and increased yaw stability. This result may be due to trade-offs incurred between the yaw stability contributions from lift and induced drag on the wings (refer to Pearson and Jones [94] for details). These complex results highlight that morphing between high dihedral angles as observed in some bird species may not necessarily follow traditional analytical expectations due to non-linear aerodynamic effects.

Finally, when discussing lateral static stability, it is interesting to note that many bird species fly with a high-wing configuration, which theoretically improves static roll stability [29]. Yet, gliding raptors fly with a shoulder anhedral angle, which would likely counteract the stability gained from their high wing configuration [70,81]. However, during the banked turn of the steppe eagle, Gillies et al. [14] could not identify any specific control inputs that were used to terminate the turn. This lack of input led the authors to suggest that the eagle was statically stable in both roll and yaw due to a combination of wing dihedral and sweep providing adequate yaw stability [79]. It is important to note that the effects of different wing configurations on static stability are not necessarily additive in nature and, as demonstrated in the previous paragraph, likely have non-linear characteristics. Therefore, it will be critical to use engineered models to explore the implications of coupled effects of wing placement, dihedral, sweep and tapering characteristics on lateral stability to advance our understanding of avian flight.

Gull-Wing Configuration

Another degree of freedom that could be leveraged for lateral control is that provided by gull-wing morphing. Due to the orientation of the wings, it is likely that asymmetric gull-wing configurations produce less net side force than a shoulder-inspired joint alone (Fig. 4). For a UAV with a constant chord, the aerodynamic forces acting on the outboard (distal) section of the wing can create a larger rolling moment than the forces acting on the inboard (proximal) section due to the larger moment arm. Therefore, if a section of the wing at the wing tip is held at a dihedral angle this can have a larger influence on the total rolling moment than the same size of section at the wing root. Note that this type of control will likely be less than if the entire wing was held at a dihedral angle at the root as discussed previously.

Interestingly, Obradovic and Subbarao [95] found that asymmetrically adjusting the gull-wing configuration provided a higher rolling moment than ailerons without increasing induced drag. The authors suggested that this response reduces the roll-yaw coupling. Using analytical models, Abdulrahim and Lind [84] estimated that their positive gull-wing configuration was slower to reach a steady-state roll after a disturbance when compared with a planar-wing configuration. Flight tests revealed that positive gull-wing configurations were less responsive to lateral-directional commands initiated using wing twisting although the sensitivity increased with bank angle [84,88]. However, Abdulrahim [88] experimentally found that morphing their UAV into a gull-wing shape improved handling qualities and control provided by conventional ailerons during a climb. Note that in that work the gull-wing configuration was not used to directly provide flight control, but was instead useful for enhancing the aileron control effectiveness.

Gull-wing designs gain an additional benefit of being able to provide a wide variety of functionality because two degrees of freedom (shoulder and mid-span) can be morphed. For example, simulations by Abdulrahim and Lind [96] found that one positive gull-wing configuration (with 5° inboard and −10° outboard angles) offered the greatest maneuvering potential (i.e., large control power and quickly converging dynamics) and morphing into a negative configuration (with −25° inboard and 25° outboard angles) would improve performance in a steep descent. However, previous experimental work by these authors found that a positive gull-wing configuration (with 15° inboard and −15° outboard angles) reduced the damping due to a pulse in the rudder [84], which would likely have a destabilizing effect on the Dutch roll mode and contrasts with the quickly converging dynamics presented in the numerical work. These discrepancies between experimental and numerical dynamic results warrant future studies to further explore the implications of gull-wing morphing on the dynamic response of a UAV.

The possible multi-functional response of gull-wing morphing suggests variable-dihedral control could be especially advantageous for aircraft that must satisfy multiple disparate mission requirements. Evidence of the multi-functional capabilities of gull-wing dihedral morphing were also provided by a lifting-line analysis of a mid-span (i.e., wrist-inspired) joint that also had asymmetric ailerons [97]. The authors found that the bank angle required to sustain a coordinated turn decreased at large anhedral angles. Additionally, large anhedral angles reduced the load factor (lift force divided by weight), albeit at the cost of a reduction in lateral maneuverability, defined as an increased turning radius and decreased turning rate. Cuji and Garcia [97] suggested that this morphing aircraft could use a planar wing configuration to gain more lateral maneuverability and could then deflect the wrist-inspired joint downwards for improved coordinated turns. In contrast, Abdulrahim and Lind [96] estimated that the optimal configuration for their UAV in maneuvering flight (large control power and quickly converging dynamics as before) was a positive gull wing configuration (with 5° inboard and −10° outboard angles). In addition, Obradovic and Subbarao [95] found that maneuvering flight with gull-wings was energetically expensive due to increased actuator loading and may be undesirable in comparison to in-plane morphing. These varied results highlight the challenges of comparing and evaluating aircraft maneuverability across studies because maneuverability can be defined differently for each study. Future work is necessary to directly contrast these different methodologies.

Additional benefits may be gained by integrating gull-wing morphing with sweep morphing. In an effort to couple the functionality of Abdulrahim and Lind [84]'s WhoopingMAV with the sweep morphing of Grant et al. [44]'s UAV, Grant et al. [74] used a vortex lattice code to predict the control available using the dihedral morphing of Abdulrahim and Lind [84]'s UAV and the sweep morphing of Grant et al. [44]'s UAV. This numerical study suggested a few unique configurations that could be used for improved steep descents and sensor pointing. Of note, the wing with the maximum amount of dihedral at both the shoulder and wrist joints that was swept backwards was identified as the configuration that would provide maximum descent angle and the fastest rate of descent. Such a configuration is similar to wing shapes used by gliding pigeons [74].

Studies on gull-wing dihedral morphing also found that the wrist-inspired dihedral morphing contributed to static lateral stability [96]. The roll stability produced by a gull-wing configuration depends on the distribution of dihedral and the resultant loads along the wing. Because the dihedral at the tip of the wing can have a larger influence on the total rolling moment, this can also lead to a larger influence on the roll stability due to the relationship between the rolling moment and the sideslip angle [78]. Similar to a shoulder-joint inspired wing, the total amount of yaw stability provided by a gull-wing configuration will depend on the axial position of the wing relative to the center of gravity. Using a vortex-lattice code, Abdulrahim and Lind [96] estimated that their UAV would be statically stable in yaw for all gull-wing configurations but that the roll stability would depend on the wing configuration. The positive gull-wing configuration was more stable in yaw than the negative configurations, but became unstable in roll. Additionally, the most laterally stable configurations had dihedral angles at each joint that were equal in sign. In other words, the cases with the most total dihedral produced the most roll stability, as expected from theory [29,78]. These configurations are more akin to a shoulder-inspired joint than the opposing angles used in gull-wing configurations. Thus, the static roll stability provided by gull-wing configurations will likely be a lower magnitude than that achieved with a single degree of freedom shoulder-inspired morphing wing with the same dihedral angle at the root.

Articulated Wing Tips

Articulated wing tips are another method of morphing control that adjusts the wing dihedral angle at some mid-span position. This method of wing morphing is often inspired by large birds such as hawks and eagles whose primary feathers flex upwards in flight (Fig. 2) [72,98]. However, akin to camber morphing, primary feather-tip morphing is a passive mechanism that is not actively controlled by birds [98]. To this end, a scaled model of AlbatrossONE that was designed and flown by Airbus showed that semi-aeroelastic hinges on its wing tips provided passive load alleviation in flight [99]. However, these wing tips, like avian primary feathers, do not provide active flight control.

NASA developed the Spanwise Adaptive Wing (SAW) that has articulated wing tips intended for active flight control [100]. This project has shown promise for effective use of articulated wing tips for large-scale aircraft control and is being developed for supersonic flight. A numerical and experimental study on a flying wing operating at a Reynolds number similar to birds estimated that actively articulated wing tips could feasibly provide effective longitudinal and lateral control [101]. Yet, the authors indicated that further work was needed to directly compare the novel control method to conventional control surfaces. Similarly, Mills and Ajaj [102] found that articulated wing tips were effective for lateral control but could not replace conventional ailerons due to a strong dependence on angle of attack, which led to roll reversal at negative angles of attack.

The static stability of a flyer will be affected by deflecting the wing tips. Preliminary work on a bird-scale delta wing found that increasing the deflection of the wing tips decreased the static stability of the aircraft without substantially affecting the lift characteristics [103]. In contrast, simulations on a RC trainer aircraft found that increasing the winglet deflection improves the longitudinal stability although the additions of winglets did serve to reduce the baseline stability [104]. This study also showed that upwards deflection reduces the static yaw stability and increases the static roll stability, similar to the theoretical expectations for full-wing dihedral morphing [29]. Note that a preliminary analytical lateral analysis found that articulated wing tips had a destabilizing effect on the spiral mode [104,105].

Articulated wing tips can also be implemented as multiple wing-like structures, known as split wing tips. Multiple performance benefits have been associated with these wing shapes including reduced induced drag and increased maximum lift; however, this comes at the cost of an increase in parasitic drag [106,107]. Actuation of such devices have yielded promising results for control in all axes but, again, future work is required to perform a direct comparison to conventional control surfaces [108].

2.4. Wing twist

In this review, wing twist refers to a spanwise variation in the wing's geometric angle of attack (Fig. 1e), while wing incidence is a solid body rotation of the wing about the y-axis. Both mechanisms change the wing's angle of attack either locally (twist) or globally (incidence), which affects the lift and drag production by shifting the zero-lift angle of attack [27]. Note that this is, in essence, similar to the effect of camber morphing, but we differentiated wing twist from wing camber morphing as follows: wing twist is geometric twist within the wing (i.e., camber line shape is constant) whereas wing camber morphing is a direct shape change to the camber line.

Birds can adjust their wing incidence by supinating (increasing the angle of attack) or pronating (decreasing the angle of attack) at their shoulder joint. They can also twist their wing either passively, due to feather flexibility, or by actively supinating/pronating at a skeletal wing joint [32,69]. The ability for a bird to change the angle of attack of different wing sections [14,71,109] led Bilo [15] to conclude that the wing could possibly function as a variable-length aileron. Cheney et al. [81] found that two of three raptor species varied their wing twist significantly as wind speeds changed but did not tend to rotate the shoulder relative to the body across a range of low-speed, steady gliding flights. Thus, these birds in slow gliding flight were largely adjusting the wing twist rather than the wing incidence. For this reason, and because most UAV designs have implemented twist morphing rather than incidence-only control, twist morphing remains the focus of this section.

Twist morphing is possibly the oldest form of avian-inspired wing morphing. Wilbur Wright hypothesized that buzzards twisted their wings in flight to gain lateral balance and later implemented controllable twist on the Wright flyer [1,12]. Accordingly, the "kinematically compact" nature of twist morphing has been proposed to require less forces to actuate than the full structural change required with avian-inspired flexion/extension [69]. The simplistic nature of wing twist morphing in comparison to other forms of avian-inspired morphing has led to the incorporation of this method of flight control on many UAVs. Like the Wright brothers' design, a large portion of UAVs with controllable wing twist use membranes or flexible materials on their wings to allow a continuous twist. Although this is possibly similar to the flexibility within avian wings, in this survey, we limited our scope to discuss the estimated aerodynamic effects of the geometry change induced by twist only. We refer to the readers to Shyy et al. [21] for a review of wing twist designs that incorporate the effects of aeroelasticity.

2.4.1. Longitudinal

Traditionally, wing twist is used to tailor the lift distribution to maximize efficiency, yet symmetric wing twist can also provide some degree of longitudinal control by affecting the lift generation. Rodrigue et al. [110] used shape memory alloys (SMAs) to twist the distal section of a wing, which increased the lift-to-drag ratio while operating at low angles of attack. However, the lift coefficient was only marginally larger than the planar wing, and thus would likely yield low pitch control effectiveness. Tran and Lind [111] studied morphing wings using a vortex-lattice method and found that a wing with opposite signs of twist and dihedral (i.e., positive twist and negative dihedral) is longitudinally stable. The study also found that adjusting the twist would have a minimal, but noticeable, effect on the stability. To this end, Tran and Lind [111] suggested that wing twist could effectively control the longitudinal static stability or static margin of the wing, although the control effectiveness would reverse signs based on the wing's dihedral angle. As a whole, the potential benefits of wing twist morphing for longitudinal control are seemingly less pronounced than the benefits to lateral control. Thus, most UAVs with morphing wing twist have largely focused on lateral control.

2.4.2. Lateral

Since the Wright brothers, multiple designs have demonstrated that twist morphing can be an effective method of lateral flight control [111–115]. One of the first bird-scale UAVs with twist control was designed by Abdulrahim et al. [113] and had wings composed of carbon fiber strips covered by a nylon film. Twist was actuated with a rigid torque rod installed directly onto the lower wing surface. With their experimental setup, wing design, and cases considered, it was found that asymmetric wing twisting in flight provided twice the maximum roll rate than permitted by conventional ailerons. Further, the authors found that there was no control reversal while approaching stall conditions and that the roll-yaw coupling was reduced during a roll maneuver [113]. Guiler and Huebsch [114] performed a wind tunnel study of a single highly-swept wing with actively-controlled tip twist and also found substantial control over the rolling and pitching moments; however, twist morphing in this configuration produced lower magnitude moments than those from an equivalent elevon (wing-tip flap) [114].

Analytical studies have also been used to consider optimal distributions of wing twist and optimal placement of ailerons for lateral control on planar wings. Hunsaker et al. [116] developed a relationship based on lifting-line theory to estimate the twist configuration that minimized the induced drag of a wing for a prescribed rolling moment over a wide range of wing planforms and aspect ratios. This study showed that continuous twist distributions with the maximum twist located between 60 and 95% of the span result in the lowest induced drag for roll initiation and that a linear twist distribution minimizes induced drag for a steady rolling rate [116]. Closed-form solutions for the minimum possible induced drag for a given rolling moment and/or rolling rate were included, as well as the resulting adverse yaw.

A follow-on study to this work considered the optimum size and placement of conventional ailerons to minimize induced drag, and compared the results to the induced drag produced from the optimum continuous twist distributions for the case of roll initiation [117]. Results from that study show that induced drag is minimized by using ailerons extending from about 30% of the span out to the wing tip over a wide range of wing designs. Even with this optimal placement, all aileron designs for common planforms considered in this study had between 4 to 20% higher induced drag than the optimal continuous wing twist configuration. Additional analytical studies leveraging lifting-line theory have shown that the yawing moment developed by wings in a pure roll can be controlled using a continuous twist distribution, but results in a substantial induced-drag penalty [118,119].

Along a similar vein to the analytical work, a follow-on study to Abdulrahim and Lind [84]'s experimental work used an aeroelastic model to show that roll rates could be maximized if the torque rod was installed between 70 to 80% of the wingspan [120]. They also noted that there was a direct trade-off between the maximum roll rate and the aerodynamic efficiency attainable due to the high drag produced by the more twisted configuration. Note that, similar to Brincklow and Hunsaker [117]'s results, it is possible that this drag is still lower than that produced by a conventional control surface. This is supported experimentally by Guiler and Huebsch [114], who found that, for a given magnitude of developed moment, the twisting design tended to have a lower drag production than an elevon.

Intriguingly, these previous experimental, numerical, and analytical studies that have identified an optimal maximum twist location along the wingspan provide a unique analogue to avian wings. Similar to the torque rod, birds' wing bones only extend a certain length of their total wingspan (Fig. 2). Therefore, it may be the case that the amount that a bird's skeleton extends into the wingspan will impact the maximum available roll rates and aerodynamic efficiency. Confirming this predication and exploring its implications will require a directed study and may not necessarily be accurate for birds because of substantial material and structural differences between engineered and biological wings.

Nevertheless, biologists have hypothesized that birds use asymmetric twist to maneuver. In particular, two methods pertaining to wing twist (or wing incidence) have been proposed for avian bank angle control [69]. First, a bird could decrease the wing twist (and thus reduce the lift) on the wing interior to the bank, which creates a rolling moment that could initiate a banked turn. The other option could be to increase the wing twist until the interior wing is stalled to use the high drag and low lift to initiate a banked turn [69]. Durston et al. [70] observed gliding barn owls using asymmetric twist during rolling maneuvers while Gillies et al. [14] observed asymmetric twist in a gliding steppe eagle during banking turns. However, as previously noted, it is unlikely that birds use a single degree of freedom at a time for flight control.

To this end, multiple UAVs have shown that wing twist can be effectively used in concert with dihedral control [84,85]. Tran and Lind [111]'s numerical results found that the static yaw stability of a UAV was dependent on both the dihedral and twist angle and that the stability was maximized using a combination of positive twist angles and negative dihedral (anhedral) angles. As previously discussed, the dihedral's effect on the static yaw stability is a function of the wing's distance from the center of gravity. Conversely, static roll stability largely depended on the dihedral angle and was independent of the wing twist [111]. Further investigations of dihedral-twist coupling are required to further explore these effects for arbitrary wing configurations.

2.5. Alula

The alula is an actively controlled digit (digit I, Fig. 5) with multiple attached feathers. The digit is often likened to the human thumb, although whether or not it is directly homologous has been a subject of debate [121]. For simplicity, we labeled this digit I following Hieronymus [38]. Birds can actively move this digit, but it is not currently known whether birds will actively actuate this digit in flight or if it is only passively deployed [122]. Alvarez et al. [123], and Austin and Anderson [124] identified that a prepared wing specimen's alula passively deploys and, eventually, passively retracts at high angles of attack. However, Carruthers et al. [59] found evidence from studies on a live steppe eagle that there may be a two-step process where the initial deployment is passive but the retraction is actively initiated, possibly allowing the alula to be retracted at lower angles of attack than allowed by the passive retraction noted by Austin and Anderson [124].

The aerodynamic function of the alula is another long-standing debate within the avian flight community [49]. Some of the first studies suggested the alula functions as a slat (serving to energize the boundary layer) [123,125,126], while more recent studies have suggested that it functions to generate and stabilize a streamwise vortex [59,127] or induce a spanwise vortex [128]. Finally, because these functions are not mutually exclusive options [49], others have suggested it functions both as a slat and a vortex generator [129]. Despite the differences presented by these studies, it is widely agreed that the alula is a high-lift device that operates in post-stall and deep-stall flight regimes [49, 59,123,125,127–129] and some experiments have found that the alula actually decreased the lift in pre-stall regimes [128,129].

Although the alula largely affects aerodynamic performance, we included the alula in our review because of its potential for active flight control [130]. Linehan and Mohseni [128] found that asymmetrically deploying the alula on either side of a wing with unit aspect ratio could allow roll control comparable to equivalent ailerons. This control is despite the wetted area of the alula being lower than the aileron. Varying the position of the alula-inspired device along the wing's leading-edge (both using a single alula and one on both wings) led the authors to conclude that a more proximally located alula has a stronger effect on the generated lift and roll. This led Linehan and Mohseni [128] to suggest a sliding mechanism to adjust the alula and, consequently, its control authority. Note that the alula position remains fixed on an individual bird and tends to be located proximally, between 30 to 50% of the span [123].

There is little reference in the literature to birds deploying their alula asymmetrically, yet these insights may offer an alternative control mechanism to an avian-inspired UAV. It is also possible that

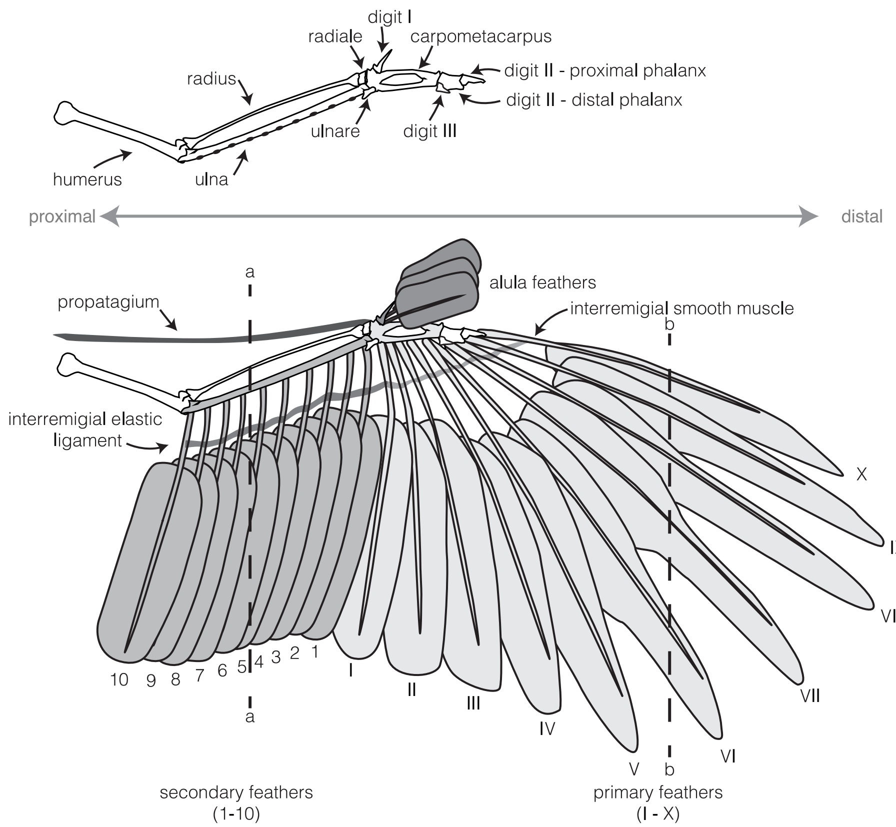

Fig. 5. Simplified anatomical drawings of a bird's wing bones and feather attachments based on a turkey vulture (*Cathartes aura*). The musculature is not included for clarity. This anatomical view is for reference only, as there is a lot of diversity in bone and feather shapes. The proximal airfoil shape (dashed line, a–a) differs substantially from the distal airfoil shape (dashed line, b–b).

an alula-inspired device may provide an active mechanism to effectively control lift generated post-stall [128,129,131]. However, the effectiveness of such a specific control mechanism in comparison to conventional controls has not yet been investigated.

2.6. Wing camber

Like aircraft, bird wings are often positively cambered, which allows increased lift generation and a positive lift force at 0° angle of attack [27,28,132]. For the inboard (proximal) section of the wing, the trailing-edge camber is dependent on the geometry of the flight feathers while the leading-edge camber is dictated by the propatagium and musculature along the major bones (Fig. 5, dashed line a-a). In contrast to the proximal wing airfoil shape, the outboard (distal) wing section's airfoil shape is entirely dictated by the geometry and positioning of the primary feathers (Fig. 5, dashed line b-b). As such, avian wing camber varies substantially along the span of the wing [133–135].

The main flight feathers (also known as remiges) include the primaries and secondaries, which are attached to the bones and each other via a complex system of ligaments, tendons, and muscles. Primaries are distributed along the length of the carpometacarpus and onto the digits. They are numbered from the most proximal to the most distal feather (Fig. 5, I–X). Secondaries are attached to, what are effectively, protrusions on the ulna and are numbered from the most distal to the most proximal feather (Fig. 5, 1–10). Different species of birds have different amounts of secondary and primary feathers.

Feathers are discrete, porous structures that are joined together to form a continuous lifting surface. Müller and Patone [136] showed that the difference in porosity between the inner and outer vane of the feathers may play a role in maintaining a continuous surface and preventing the feathers from separating under aerodynamic loads.

The system of ligaments, tendons, and muscles that connect the flight feathers to the wing structure is complicated and varies species-to-species. In part, the secondary feathers are attached together at their shafts with an interremigial elastic ligament, which allows the flight feathers to move in sync as the wing extends and contracts (Fig. 5) [38]. These are, in turn, connected to the primaries, which are interconnected with a band of smooth muscle (involuntary muscle). In some species, such as the pigeon, there is an additional feather known as the carpal remex onto which the ligament connecting the secondaries and the smooth muscle connecting the primaries both attach [38]. We refer the reader to Hieronymus [38] for detailed anatomical schematics of a pigeon's wing muscles, ligaments, and flight feather attachments. A recent study showed that severing the connecting material running between the flight feathers leads to a loss in the continuous lifting surface [137]. This study led to the design of a feathered morphing wing UAV [33] (discussed in Section 2.2), which maintained an effective lifting surface with elastic bands serving as the interremigial connections.

Feathers themselves are composed of keratin similar to, but distinct from, human hair and nails [138]. They do not possess any musculature which could generate active camber control of the trailing-edge. However, for the proximal wing, the cross-sectional profile of the propatagium, and hence the airfoil's leading-edge shape, has been observed to lengthen by up to 30% and slightly thicken as the elbow angle is reduced [139]. Note that this shape change is coupled with elbow joint extension and has not known to be independently controlled. It has also been suggested, based on numerical simulations of the house sparrow *(Passer domesticus)*, that the propatagium may produce the majority of the wing's lift [140], but this has not been validated. Yet, as an airfoil's lift is known to be dominated by high pressure towards the leading-edge [28], it is likely that the combined camber induced by the propatagium, skin, and musculature at the

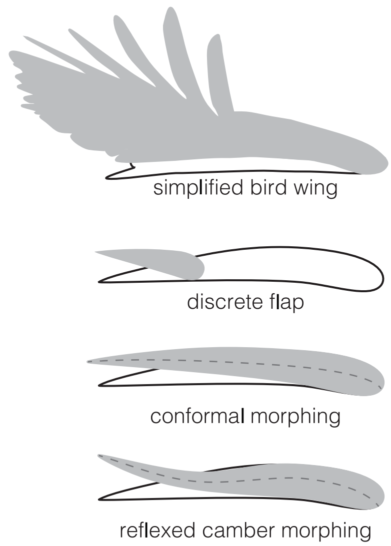

Fig. 6. Simplified renditions of the different UAV implementations of avian-inspired wing camber morphing.

leading-edge of avian wings plays an important role in lift generation. Finally, in-flight measurements of wing geometry have indicated that the wing camber does not remain constant with speed, and observations of this shape change can provide insight for engineers [133,135,141].

An airfoil's continuity, provided by many camber-morphing wing designs, plays a crucial role in actuator effectiveness, drag reduction, and efficiency. Unlike traditional actuation mechanisms, which rotate a rigid aileron or flap about a hinged point, camber-morphing airfoils exhibit smooth transitions in camber. These differences are demonstrated in Fig. 6. Not only have these camber-morphing airfoils (often referred to as conformal flaps) been shown to produce more lift than their traditional counterparts given the same amount of tip displacement [142–144], but they also can produce less drag, making them more efficient as well [143,145]. However, much of the challenge of camber-morphing (or variable-camber) aircraft lies in the design complexity and innovative implementation of such mechanisms.

2.6.1. Camber morphing mechanisms

As the use of camber-morphing wings has received a lot of attention historically, current research primarily targets resolving the structural and control challenges in addition to implementing innovative methods of utilizing camber morphing. Engineers must balance and prioritize the need for high bandwidth (rapid actuator response time), high force output, low profile or footprints (small size), low weight, large deformation or strain, and low cost. Actuators that can operate at high bandwidths are desirable for rapid aerodynamic maneuvers as they provide a fast control response. High force outputs enable the actuator to withstand larger aerodynamic loads and consequentially are suitable for larger aircraft. Actuators with low profiles or footprints not only take up less space, but they also tend to be lightweight, which maximizes aircraft fuel efficiency. Lastly, while the effects of low deformation or strain on the aerodynamic performance is dependent upon how the actuator is integrated, broadly speaking, larger deformations and larger strains generate larger aerodynamic control forces and moments.

These vast trade-offs in camber-morphing actuation mechanisms can influence the resulting aerodynamic performance, especially considering there is a delicate interplay between aerodynamic loads, structural deformations, and dynamic effects. While the focus of this work is specifically on the aerodynamic control capabilities of avian-inspired morphing mechanisms, the purpose of delving into the mechanical details of these actuators is to detail the advantages and disadvantages of common actuators, and to illuminate the stark differences in technological readiness between camber morphing and the other modes of bio-inspired morphing discussed in this review. For detailed information on the many mechanisms developed for UAVs with camber morphing refer to reviews by Barbarino et al. [12], Sofla et al. [146], and Gomez and Garcia [147].

Some of the first camber-morphing wings relied on traditional actuators like hydraulics, linear actuators, and servo-pulley systems which tend to be cost effective, exhibit high force output, and generate large displacements. These actuators enabled initial camber morphing development of both leading- and trailing-edge mechanisms to be conducted on large-scale aircraft, such as the Mission Adaptive Wing (MAW) and the Flexsys Mission Adaptive Compliant Wing (MACW) [148–150]. Though these initial camber-morphing aircraft far exceed the size and flight speeds of birds, their notable improvements in aerodynamic efficiency (quantified by lift-to-drag ratio) motivated future research at smaller scales. Camber-morphing designs that followed incorporated similar systems, which generated smooth variations in leading- or trailing-edge camber through a series of hinged joints [151], inherent flexibility of ribbed structures [152–154] (such as Woods et al. [145]'s FishBAC design), or through deforming a composite skin using an internal structural component [155] (such as the Variable Camber Compliant Wing (VCCW) design [156–158]).

With these technological advancements came the integration of smart-material actuators into camber-morphing UAV designs. In this work, we briefly discuss advances in two key actuators: shape-memory alloys (SMA) and piezoelectrics.

Shape-memory alloy, commonly nickle-titanium (NiTi), can be "programmed" to remember a shape in a cooled state and, once deformed, it can return to the initial state upon heating [159]. SMAs are compact and exhibit high actuation energy densities (actuator work output per unit volume) making them ideal candidates for applications undergoing high aerodynamic loadings. Focused on larger-scale UAVs and morphing hydrofoils for submarine applications, initial camber-morphing studies integrated thin SMA wires into compliant facesheets to simultaneously serve as the foil's skin and camber-morphing actuator [160,161]. Subsequent SMA work included aero-structural optimization [162], compliant rib structures [163], and hinged designs [164] including a unique design that incorporated magnets as a self-locking mechanism [165]. But despite the benefits of working with SMAs, they are limited by low strain capabilities and frequently suffer from low bandwidth due to the heating and cooling process required for actuation [159].

Piezoelectric actuators are another mechanism that have gained traction within the morphing community as they exhibit rapid actuation bandwidth, which makes them suitable for highly maneuverable aircraft or uncertain flow environments. Due to their rapid response and high force output, piezoelectric-driven camber-morphing designs have a rich history in rotor aircraft applications which is reviewed in great depth by Barbarino et al. [12]. Within novel UAV designs, piezoelectrics have been widely used in sandwich or bimorph composite configurations, where the strain induced by a piezoelectric layer bends the composite about the neutral axis. This concept was initially tested by Lazarus et al. [166] who conducted a parameter study and optimization on strain-induced camber-morphing actuators. One key benefit to this configuration is that the piezo-composite can serve as both the deformable wing exterior and the actuator. This functionality eliminates the need for flexible skins in many applications, which has presented a substantial design challenge for camber-morphing wings. This development inspired a new generation of thin piezoelectric actuators such as thin-layer composite unimorph ferroelectric driver (THUNDER) and macrofiber composite (MFC) actuators, which were quickly adopted into the camber-morphing discipline [167–172].

Advances in smart materials has been a turning point in morphing wing manufacturing and future work will build on the existing foundation to help support the implementation of the most beneficial aspects of avian morphing flight.

2.6.2. Longitudinal

Symmetric morphing of the total, leading-, and trailing-edge camber controls the generated lift, drag, and pitching moment. Initial research into this field focused on total and leading-edge morphing for large-scale aircraft, which paved the way for avian-inspired camber-morphing UAVs. One of the first camber-morphing airfoils was developed in 1920 by Parker [173] who designed an airfoil that changed the total camber passively in response to aerodynamic loading. This camber-morphing airfoil could transition between a high-lift cambered configuration and a low-drag streamlined configuration. Subsequent research by Secanell et al. [174] focused on airfoil geometry optimization and confirmed that total camber morphing increased performance across multiple flight conditions.

Advances in leading-edge conformal morphing (often called "droop nose" morphing) aimed to replace leading-edge slats in traditional large-scale aircraft by increasing lift generation during take-off and landing while minimizing the airframe noise associated with slats [40, 175]. Substantial research has been geared towards resolving the structural challenges associated with seamless leading-edge morphing by using structural or aero-structural optimization [155,176–178]. Aerodynamically, not only is drooped-nose morphing effective for generating large lift forces and delaying stall [179,180], but also some degree of longitudinal control of pitch and trim [181]. Though many of these findings are conducted at Reynolds numbers outside the range seen in bird flight [13], Strelec et al. [162] tested an airfoil that morphed the leading- and trailing-edges in a wind tunnel at Reynolds numbers comparable to bird flight and found that the lift coefficient increased in a morphed state. Together, these findings may provide insight as to the aerodynamic effects of proximal leading-edge shape change due to tension or relaxation of a bird's propatagium. Further studies are needed to confirm if such a leading-edge device can provide any substantial ability to control the developed lift, pitching moment and subsequently, the trim condition.

Camber-morphing trailing-edge designs have been especially popular for UAVs, as direct comparisons can be drawn to traditional control surfaces such as ailerons and articulated or hinged flaps. Sanders et al. [142] was the first to directly compare the aerodynamic performance of a conformal, camber-morphing, trailing-edge control surface to a traditional articulated control surface on a large-scale fighter jet. These simulations revealed that, when deflected equally, the conformal control surface experienced a larger pressure distribution over the airfoil when compared to the hinged design. Further, conformal morphing eliminated the pressure spike that is associated with the abrupt change in camber line caused by articulated control surfaces. This resulted in up to a 40% increase in the lift coefficient and up to a 100% increase in pitching moment magnitude. Subsequently, an inviscid study by Hunsaker et al. [144] found an analytic solution for predicting the difference in lift and pitching moment that can be expected from a conformal flap relative to a traditional flap. This analytic solution matched the computational results of Sanders et al. [142] but gave an equation that can be used for any flap-chord fraction. Results show that the change in lift and pitching moment are a strong function of flap-chord fraction and only a weak function of airfoil thickness and camber [144]. This study also showed that for most designs, a conformal flap requires between 65 and 80% of the deflection of a traditional flap to produce the same amount of lift.

Similarly for bird-scale UAVs, Woods et al. [145] measured an improvement in the maximum lift-to-drag ratio of over 20% at pre-stall angles of attack when comparing a novel, rib-based, camber-morphing trailing-edge (Fish Bone Active Camber wing - FishBAC) to a hinged airfoil at a Reynolds number of 3.9×10^5. Many other studies have verified that conformal morphing not only provides an effective method to control lift for UAVs [170], but also improves efficiency while in a morphed configuration compared to hinged designs [143,182,183]. Efficiency improvements have also been confirmed by flight tests on bird-scale UAVs by Zhao et al. [184] although the variable camber was not used as a control mechanism during those flights.

Thus far, the camber-morphing airfoils discussed have primarily implemented a single camber-morphing actuator; however, adding multiple degrees of freedom along the airfoil chord can enable reflexed-camber geometries (Fig. 6). Pankonien et al. [164] developed a camber-morphing airfoil that incorporated both an antagonistic SMA hinge and an MFC camber-morphing trailing-edge, which enabled the camber to be prescribed independently at two locations along the chord. With dual chordwise actuators, this design could not only achieve greater camber than either mechanism independently but could also generate reflexed camber. Pankonien et al. [185] numerically estimated that when both the SMA and MFC actuators were maximally deployed in a positive-camber configuration, the airfoil lift increased by 180% when compared to pure SMA induced camber, and 46% when compared to pure MFC induced camber. When actuated in a reflexed configuration and optimized to incorporate the structural properties of the SMA and MFC actuators, the airfoil generated the same amount of lift as a non-reflexed airfoil but with considerable drag reductions, hence improving the aerodynamic efficiency.

This airfoil design, which was later tested experimentally [186], may provide some insights into avian flight, since birds like the steppe eagle have a thin trailing-edge that was hypothesized to assume a shape with reflexed camber in flight [49,135,141]. Carruthers et al. [141] used simulations to compare a reconstructed steppe eagle airfoil to a S1223 high-lift airfoil and found the eagle airfoil generated lower drag across a broad range of angles of attack, which could motivate future integration of this mechanism into morphing UAVs.

Longitudinal control can also be gained through distributed actuation of multiple camber-morphing airfoils along the span of a wing. However, again most work has focused on optimizing the aerodynamic performance of these wings [187,188]. Note that this morphing is similar to variable twist distributions discussed in Section 2.4. One difference between these methods of morphing is that the airfoil camber line will be morphed as well as the twist distribution. Future research to investigate differences between these methods and how this can be extrapolated to longitudinal control is necessary.

As evidence that birds can actively control their wing camber is limited, studies on the aerodynamic effects of passive avian camber change are warranted. Aeroelastic effects on avian wing camber are due in part to the flexibility of the feathers [189]. Considering aeroelastic effects, avian wing geometries have been observed to passively decamber to produce a more streamlined profile as the flow speed increases [81, 133,135] and similar passive, aeroelastic decambering has also been hypothesized to play a role in aerodynamic load alleviation [91,190]. In UAVs, camber morphing has been demonstrated as a useful method of tailoring flight across a range of flight speeds and may actively provide some longitudinal control. Additionally, flexible-airfoil UAV studies have observed additional benefits such as damping of aerodynamic disturbances [191], delay in stall [192,193], and increased efficiency (due to a reduction in drag) [192–194]. In all, aeroelasticity remains an active field of research, and further understanding how this impacts aerodynamic control maneuvers in birds and UAVs is required.

2.6.3. Lateral

Asymmetric camber morphing, although not a known method of avian flight control, can be directly contrasted with the lateral control provided by ailerons. Studies on large scale aircraft by Sanders et al. [142] found that conformal control surfaces exhibited 25 to 30% larger maximum roll moments and consistently larger roll rates than their hinged counterparts. However, one of the drawbacks included a reduction in the reversal dynamic pressure, meaning control reversal would occur at lower angles of attack than for an equivalent hinged design. Later numerical research by Previtali et al. [195] also found that an asymmetric camber-morphing wing produced roll moment coefficients twice as large as those required to maneuver small aircraft while experiencing a substantial reduction in drag when compared to the conventional hinged actuator. The simulations of Previtali et al. [195]'s camber-morphing mechanism were later advanced by Molinari et al. [196] who validated the results of their model with experimental wind tunnel and flight testing. Intriguingly, a membrane-wing MAV reinforced with rigid batons and actuated with a torque rod [197] obtained over six-fold greater roll rates than Sanders et al. [142], which demonstrates the versatility of this mechanism across an array of aircraft scales.

With multiple camber-morphing actuators, spanwise wing geometry can also be optimized for lateral control maneuvers. Molinari et al. [172] performed an aero-structural optimization of a camber-morphing wing with MFC and dielectric elastomer actuators at a Reynolds number comparable to larger birds [13]. The internal rib structure of the trailing-edge was optimized, at multiple locations along the wingspan, to maximize the roll coefficient with actuation that provided sufficient rigidity to withstand the expected aerodynamic loads. At the design condition, the optimized wing experienced an 18% increase in aerodynamic efficiency compared to a rigid elliptic wing. Similar spanwise optimization of a camber-morphing wing was conducted by Keidel et al. [198], who demonstrated that the spanwise-optimized morphing wing was capable of roll, pitch, and yaw control on par with conventional control surfaces. This wing also achieved a 12% improvement in drag during cruise conditions. In addition, a preliminary study by Montgomery et al. [199] showed that conformal lateral control surfaces could be analytically optimized to minimize induced drag as well as numerically optimized to minimize total drag.

Another key finding from Keidel et al. [198]'s work was that the airfoil camber along the span could be optimized in a roll maneuver to reduce roll-yaw coupling and thus reduce the effects of adverse yaw. Note that this is a similar result to Hunsaker et al. [118]'s analytical results for twist which was discussed in Section 2.4. Collectively, these studies highlight the potential benefits that optimization studies can provide for morphing wing designs.

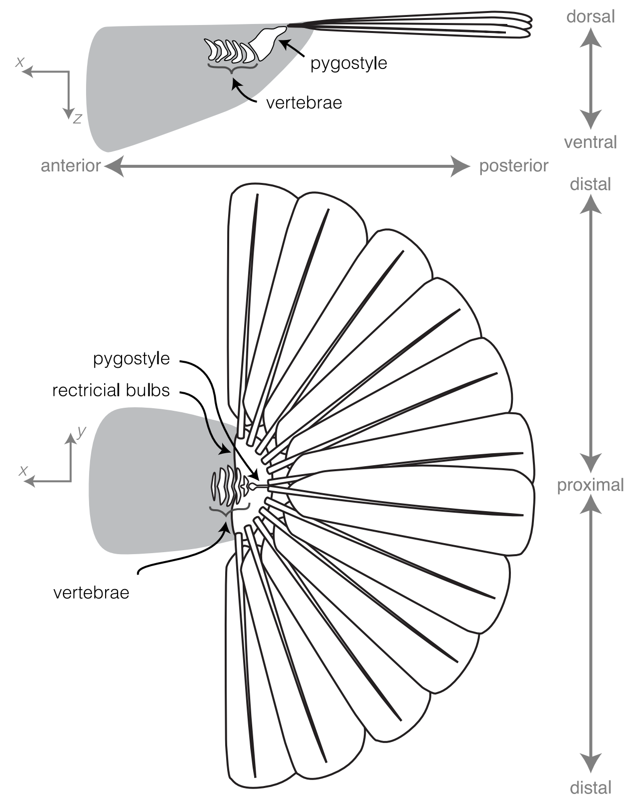

Fig. 7. Simplified anatomical drawings of a bird's tail. The musculature is not included for simplicity. This anatomical view is for reference only as there is a lot of diversity in bone and feather shapes.The lateral view was adapted from [200] and the dorsal view was adapted from [201].

3. Tail morphing

While both aircraft and birds have a controllable tail, the appearance and function of each can differ. Traditional aircraft incorporate both a vertical and horizontal tail mounted at the end of the fuselage. Each of these lifting surfaces use control surfaces, known as a rudder and elevator respectively (Fig. 1), to provide control during flight. These controls typically rely on rigid, hinged motion and only deflect a portion of the rigid stabilizers onto which they are installed. Unlike traditional aircraft, a bird's tail is composed of a single surface that can be adjusted continuously during flight through multiple degrees of freedom including incidence, rotation, and spread angle (Fig. 1e) [14,72,202].

Before discussing the aerodynamic implications of tail morphing, it is helpful to first review the anatomy of a bird's tail. A bird's tail is composed of a musculoskeletal system with embedded tail feathers known as rectrices (Fig. 7). The skeletal system has multiple vertebrae and ends in a pygostyle, which is a bony fusion of a few of the final vertebrae. Structures known as rectricial bulbs attach to either side of the pygostyle and each tail feather is embedded into these structures, with the exception of the two most central feathers, which are attached directly to the pygostyle [201,203]. The number of tail feathers varies between different species, for example pigeons have twelve (12) and turkeys have eighteen (18) [203]. A pigeon tail is visualized in Fig. 7. The tail structure is largely controlled by 6 major muscles [204,205] and, intriguingly, there is evidence that the tail is both anatomically and functionally decoupled from the rest of the trunk and hindlimbs [205]. This decoupling suggests that the tail can be controlled independently from the trunk and hindlimbs and thus may be specialized for flight control. Further anatomical details are available in studies by Baumel [204] and Gatesy and Dial [205].

Traditionally, an aircraft's tail is discussed relative to its important role in maintaining pitch stability. In particular, an aircraft's horizontal stabilizer is necessary to achieve an equilibrium position as well as to respond to disturbances in pitch in a way that returns the aircraft towards its equilibrium condition (i.e., an open loop system) [28,29]. Following this logic, Hummel [206] predicted that the removal of a bird's tail feathers would render the bird entirely unstable and require it to rely on active control to adjust to disturbances (i.e., a closed loop system).

As birds have been observed to successfully fly without their tails, avian tails likely serve many functions and may not be necessary for successful flight [11,206,207]. For example, Hankin [207] observed that a tailless green parrot (*Palceornis torquatus*) appeared to fly while flapping without difficulty, but over-rotated in the pitching axis while attempting to perch. This rotation is consistent with a lack of pitch control, suggesting that the tail's control of the pitching moment is important while landing. Furthermore, experimental studies on gull wings have suggested that a gull would be statically stable without a tail [31,39]. This expectation was extended to an inertially-informed analysis that revealed that 21 of 22 investigated species are likely capable of stabilized flight without a tail [63]. However, the gull models were not capable of achieving a trimmed (equilibrium) flight condition and thus, would need an additional controllable degree of freedom, possibly provided by the tail or shoulder angle, or to adjust their wing and body configuration to be unstable and instead use active flight stabilization [39]. This result again highlights the importance of the tail for flight control.

Our review identified many areas for future research which include determining the effects of small-scale transient morphing [14,208] and passive tail deformations due to feather flexibility [190]. Further, few engineering studies have implemented an avian-inspired tail with the ability to control the incidence, spread, and rotation angle simultaneously. One explanation for this specific absence of research is that avian tails lack a vertical stabilizer, which aircraft typically rely on for yaw stability and control [26]. While this may be an initial hurdle for aircraft that incorporate avian-inspired tail morphing, analytical results supported with numerical simulations suggest that birds' wings and body may provide sufficient dynamic and static yaw stability due to the small relative size and inertia of birds [77,209,210]. Despite the challenge of generating sufficient yaw stability without a vertical tail, avian-inspired tail actuators have begun to appear in recent engineering research.

In the following sections, we investigated the flight control afforded by morphing the tail incidence angle (Section 3.2), spread angle (Section 3.3), and rotation angle (Section 3.5) as reported in avian-inspired UAV studies. In addition, to provide insight into how tail shape may affect control, we discussed the effects of forked tails or streamers (Section 3.4). Note that there is evidence that birds can also laterally shift their tail in flight, usually through a solid body rotation about the z-axis [14]. We did not include this degree of freedom due to a lack of detailed biological studies or UAV designs quantifying the effects of a lateral tail motion.

3.1. Tail morphing mechanisms

The Lishawk is perhaps the most advanced morphing UAV design to incorporate a morphing tail, having progressed through design, analysis, and flight-testing phases. Developed by Ajanic et al. [48], the Lishawk design has three degrees of freedom of tail morphing including tail spread, incidence, and lateral deflection about the z-axis, defined in Fig. 1. Control is gained with multiple survey-linkage mechanisms that actuate artificially constructed tail feathers [48]. In addition, the Lishawk is outfitted with a morphing wing sweep mechanism, which was discussed in Section 2.2. Unlike birds, this design incorporated a vertical stabilizer on the top and bottom of the horizontal tail.

Zheng et al. [211] designed and manufactured a morphing tail with three degrees of freedom including tail spread, incidence, and rotation about the x-axis as defined in Fig. 1. The tail design used by Zheng et al. [211] has a structure like the LisHawk including overlapping feather-like features, although the tail has a forked shape. To date, only preliminary simulations have been performed with this tail mechanism [211].

Ajanic et al. [48] and Zheng et al. [211] employed systems with three degrees of freedom; however, morphing tail designs with only two degrees of freedom have also been examined. These include Parga et al. [212]'s V-tail design with rotation and incidence angle control provided by a rack and gear system. Morphing tail designs implemented by Gamble and Inman [213] and Perez-Sanchez et al. [214] employed macrofiber composites (MFCs), a thin smart material actuator that couples the strain-inducing properties of piezoelectric materials with the bending behavior of composite laminates. Gamble and Inman [213]'s design used MFCs integrated in the structure of a triangular tail to non-linearly couple tail bending and twisting. Although this tail can assume a similar shape to the passive response seen in bird's tail feathers under aerodynamic loading (bent up at the tips), the material was rigid in response to aerodynamic loads. Perez-Sanchez et al. [214]'s tail installed MFCs along the length of a non-rigid triangular tail, which controlled the curvature on either side of the tail. Both designs allowed for symmetric and asymmetric morphing.

3.2. Tail incidence

Among the degrees of freedom offered by bird tails, tail incidence bears the greatest resemblance to the modes of actuation in traditional UAV designs. Both tail incidence and elevator deflection rotate a control surface about the y-axis (Fig. 8). The elevators are mounted to the horizontal stabilizer and produce moments and forces that enable longitudinal control. Horizontal stabilizers provide longitudinal stability due to their aftward position in relation to the main wing and center of gravity of the aircraft. In birds, avian tail incidence is adjusted by rotating the entire tail surface, in a manner similar to stabilators (also known as all-moving tailplanes) on fighter jets, which are used in lieu of a traditional elevator to provide enhanced maneuverability in supersonic flight [26].

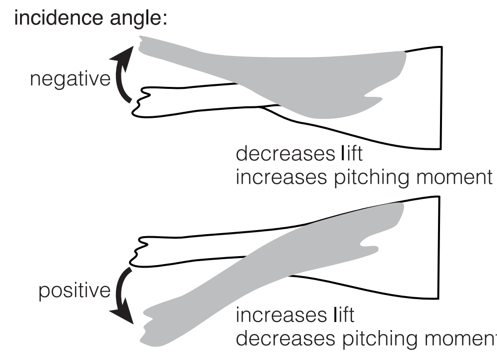

Fig. 8. Positive tail incidence caused by deflecting the tail downwards increases the lift, while negative incidence decreases the lift.

Tail control effectiveness is traditionally quantified by the tail volume coefficient (Appendix A). Due to a relatively short tail moment arm, birds tend to have a lower tail volume coefficient than traditional aircraft [63,215], which could reduce the available pitch control effectiveness and static stability [28].

3.2.1. Longitudinal

Elevators on traditional aircraft are used extensively for longitudinal control and are predominately used to control the pitching moment. A change in elevator deflection changes the lift on the horizontal stabilizer, which creates a change in pitching moment due to the moment arm between the horizontal stabilizer and the center of gravity. Within the assumptions of small deflections and small angles of attack, an elevator deflection changes the zero-lift angle of attack of the lifting surface with little change to the lift slope [28]. This allows control of the longitudinal forces and moments on the aircraft without substantially affecting the longitudinal static stability.

The function of tail incidence in birds is affected by the tail feather flexibility, swept nature of the tail, and the wing-body flow interactions due to its proximity to the main wing. The function of avian-inspired tails for longitudinal control has been experimentally studied by multiple researchers. Hummel [206] quantitatively characterized the role of tail incidence in avian-inspired UAVs by manufacturing and subsequently testing a series of rigid avian-inspired wing–tail combinations. As expected from traditional aircraft studies, Hummel noted that for a square tail with unit aspect ratio, a negative tail incidence (upwards deflection as in Fig. 8) decreased the lift produced by the model at any given angle of attack when compared to a tail with zero incidence [206]. This finding is also supported by experimental wind tunnel tests on Ajanic et al. [48]'s LisHawk tail design, Gamble and Inman [213]'s MFC tail design, and Parga et al. [212]'s V-tail design, which all demonstrated a decrease in lift force with negative tail incidence. Therefore, a change in tail incidence has a similar effect on the aerodynamics as changing the elevator deflection.

In general, a change in elevator deflection will affect the drag characteristics. The change in drag due to elevator deflection depends on the flight condition, angle of attack, and downwash from the main wing. Studies on UAVs have found that a negative tail incidence increased drag at near-zero angles of attack [48,212,213]. However, at large angles of attack, Ajanic et al. [48] found that negative tail incidence reduced drag production. Because the downwash from the main wing changes the local angle of attack of the tail, the effect of tail incidence will depend on the angle of attack of the body on which it is installed. Hence, it is important to specifically quantify the tail angle of attack in addition to its incidence when analyzing observational studies of birds.

A recent study on a barn owl gliding towards its trainer found the birds used a tail posture with approximately 26° positive incidence angle and 125° spread from tail feather tip-to-tip [216]. CFD analysis supplemented with an analytical drag model of the barn owl's tail with artificially varied incidence and spread angles suggested that this specific tail posture may serve to minimize the drag production at the given flight speed.

There has been some debate as to whether tail incidence can be used as an air brake by increasing drag when deployed at large incidence angles. Parga et al. [212] found that the tail drag coefficient (at an incidence angle of −67°) was three times as large as the drag generated by the undeflected tail. The authors proposed that the large drag increase could allow the tail to function as an air brake. Gamble and Inman [213] experimentally tested a similar hypothesis using asymmetric incidence, where one half of the MFC tail had positive incidence and the other had negative incidence. This design was intended to generate an increase in drag without also generating a pitching moment; however, their results showed that their tail did not generate a sufficient increase in drag to be used as an air brake [213]. This was hypothesized to be due, in part, to the limited actuation range of the MFCs for a tail of this size and configuration.

Although tail incidence in avian-inspired UAVs may exhibit small increases in drag that could represent similarities to an air brake, Thomas [208] presented a theoretical argument which claimed that, even if avian tail drag is overestimated, tail incidence alone would not provide enough force to act as a braking device in flight. Instead, Thomas [208] proposed that tail incidence in birds is more likely used to manipulate lift forces and pitching moments. Pennycuick and Webbe [67] also concluded, based on observational studies, that fulmars did not appear to use their tails as an air brake, and instead relied on their feet to increase drag during descent. Though most studies conclude that tail incidence serves as a relatively poor air brake, Parga et al. [212]'s contrary conclusions indicate that tail incidence may have the potential to generate sufficient air brake control, given the proper design.

For traditional aircraft, the elevator deflection or tail incidence required to trim the aircraft typically varies with speed from a negative incidence (upwards deflection) to positive incidence (downwards deflection) as speeds decrease. A similar trend was noted by Ajanic et al. [48] who found that to minimize power consumption while trimmed, and hence maximize the lift-to-drag ratio, the optimal tail incidence angle was negative at higher speeds, but gradually deflected downwards as the flow speed increased above 8 m/s (Reynolds number of 9.2×10^4). These results are similar to biological observations. Evans et al. [202] found that as flight speed increased, birds habitually reduced their tail incidence angle, approaching a configuration that is parallel to the incoming flow, while Cheney et al. [81] found that gliding raptors held their tails at a positive incidence angle at low speeds.

Positive incidence angles at low speeds increase lift production, possibly resulting in a positively loaded tail. In aircraft, if the center of gravity is in front of the aerodynamic center of a positively cambered main wing, an aircraft cannot trim with a positive lift force acting on the tail (Fig. 9a). Instead, if the center of gravity is behind the aerodynamic center of a main wing, the lift on the tail can be positive at low speeds, which is the case for some aircraft designs (Fig. 9b) [217]. Along these lines, an experimental study by Usherwood et al. [218] quantified the lift distribution on raptors in slow gliding flight and found that the tails were producing a positive lift force. If these birds were in a trimmed configuration, their results suggest that the raptors' center of gravity is behind the aerodynamic center of the wing while in low-speed flight.

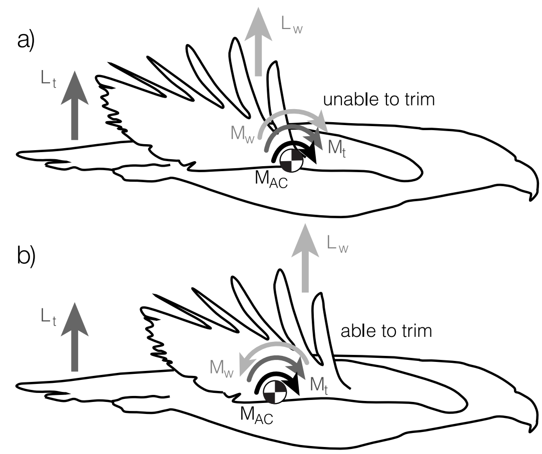

Fig. 9. Simplified visualization of avian configurations with positive tail lift. M_t the pitching moment due to the tail lift (L_t) at a moment arm, M_w the pitching moment due to the wing lift (L_w) at a moment arm, and M_{AC} the pitching moment about the wing's aerodynamic center.

The distance between the center of gravity and aerodynamic center can be shifted by adjusting inertial and/or aerodynamic characteristics. Some modern aircraft use an inertial method, called weight-shift control, to shift their center of gravity during flight by pumping fuel into aft tanks. Manipulating the center of gravity location during flight allows these aircraft to change the load on the tail required to trim, and therefore minimize trim drag [29,219]. Unlike these aircraft, recent analysis of avian inertial characteristics showed that birds are likely able to substantially shift their aerodynamic center relative to their center of gravity [63]. This revealed that 17 of 22 species had the capacity to shift between passively stable and unstable flight in the longitudinal axis through morphing their elbow and wrist alone. As noted previously, the effect of bird wing morphing on the location of the center of gravity is not substantial [63,220]. However, some birds undergo weight loss during long migrations on the scale of 1% of body mass per hour [221], which may cause a substantial shift in their inertial characteristics over the length of the flight.

As mentioned previously, deflecting the elevator shifts the pitching moment curve, which adjusts the trim angle of attack (the angle of attack where the pitching moment is zero) without substantially changing the pitching moment slope and, consequently, does not affect the longitudinal static stability [28,222]. Similar to a conventional elevator, Hummel [206] found that a negative avian-inspired tail incidence (Fig. 8) caused an upward shift of the pitching moment curve, a reduction in the trim angle of attack and did not alter the pitching moment slope.

Increasing tail incidence can be used in maneuvering flight as demonstrated by Ajanic et al. [48]. The developed pitch rate of the Lishawk due to a change in the tail incidence angle increased with increased tail spread and forward-swept wings. These results, in tandem with the knowledge that tail incidence will not substantially affect the longitudinal static stability [28,206], suggest that tail incidence can effectively be used for longitudinal control in a manner similar to a conventional elevator. However, we could not identify direct measures of the control effectiveness of avian-inspired tail to directly compare to a conventional elevator. This is an area for possible future research.

In light of this evidence, it is unsurprising that the tail plays an active role in maneuvering flight for birds as well. An observational study on the northern fulmar (*Fulmarus glacialis*) by Pennycuick and Webbe [67] noted that changes in tail incidence likely contributed to pitch control but hypothesized that, in gliding flight, any such motion would likely be small and serve a minor corrective purpose. Live birds performing landing and perching maneuvers, which require strong pitching moments, have also been observed to control tail incidence [206,208,223,224]. During a perching maneuver, Carruthers et al. [72] observed a steppe eagle deflect its tail upwards (negative incidence, Fig. 8) during the first phase of perching maneuvers, which was quickly followed by a nose-up pitching motion. In the final phases of landing, however, the tail exhibited positive incidence, which was hypothesized to be a method of increasing the lift at low speeds similar to gliding flight observations [48,218]. The authors likened this final phase of tail motion to a parachute, which provides additional drag (and lift, depending on parachute geometry) during descent [225].

Although the UAV studies discussed in this section demonstrated similar trends with regards to the lift, drag, and pitching moment response of tail incidence, the magnitude of these control maneuvers differed between designs. These differences in magnitude are in part due to variations in the tail area relative to the wing's area. As such, the incorporation of tail spread mechanisms can be used to manipulate the total tail area and hence the control forces.

3.2.2. Lateral

In the preceding discussion, we discussed the implications of tail incidence in longitudinal control; however, when coupled with tail rotation or twist, changes in tail incidence may be used for lateral control as well. Of note, Gillies et al. [14] measured the magnitude of tail deformation, including tail incidence, and found that the tail was consistently lowered (towards positive incidence, Fig. 8) at the start of banked turns, which was hypothesized to drive a nose-down pitching moment. It is likely that the role of the tail incidence in lateral maneuvering is strongly coupled to other morphing degrees of freedom. Thus, the relationship between tail morphing and lateral maneuvers will be covered in greater detail in the following sections.

3.3. Tail spread

Tail spread morphing can affect aerodynamic forces and moments by adjusting the tail shape and area. Both parameters affect the overall tail volume coefficient, where spreading the tail will tend to increase the tail volume coefficient. Increasing the tail volume coefficient will increase the pitch control effectiveness and the static pitch stability of a flyer [28]. However, the avian tail volume coefficient used while gliding with a spread tail often falls below 0.3 [215], while aircraft may have a tail volume coefficient ranging between 0.4 (fighter jet) to 1 (transport aircraft) [30].

Birds can spread their tail by activating a single muscle to actuate the rectricial bulbs [203] (Fig. 7). This, in turn, allows them to directly control the spread angle of the tail feathers. As a result, the ability to spread the tail is largely decoupled from the other degrees of freedom, which allows for a more direct comparison to UAV-like functionality. Despite this ease in comparison, few contemporary UAV designs incorporate tail-spreading control. Two notable examples of UAV designs with control of tail spread include the Lishawk, a UAV that can spread its tail symmetrically to increase the area by 214% [48], and a preliminary design by Zheng et al. [211] that has a spreadable forked tail that can increase the tail area by approximately 50%.

Yet, the Lishawk is currently the only published tail spreading mechanism that has been successfully flown and quantified. However, other engineering teams have investigated mechanisms that could effectively produce large changes in the tail area on a UAV. These studies include a single degree of freedom smart material tail with a compliant interior structure [226] and a four degree of freedom pygostyle-inspired tail that uses feather-like structures [227]. Both mechanisms were shown to actively adjust the tail shape, but their aerodynamic control capabilities were not assessed.

3.3.1. Longitudinal

Tail spread plays an important role in static lift generation in gliding flight. As discussed in the previous section, Ajanic et al. [48] found that, to generate sufficient lift to support the body weight and minimize power requirements in steady level flight at slow speeds (below 7.6 m/s, Reynolds number = 8.7×10^4 in this case), it became necessary to increase both the incidence and spread of the tail in addition to extending the wings. Note that to minimize the power required at even lower speeds (below 5 m/s, Reynolds number $\approx 5.7\times10^4$), the tail spread and the incidence angle were reduced and the aircraft had to maintain a substantially higher angle of attack (20° to 60°). These extremely low-speed and high-angle-of-attack results were also highlighted as being subject to higher error due to noisier measurements [48]. The results from the Lishawk at low speeds and low angles of attack can be directly compared to observations of many species of birds that spread their tails as their gliding speed slows, which has been hypothesized to provide additional weight support and minimize drag (and thus power requirements) [11,53,54,56,67,81,205,216,228,229].

Data from the Lishawk revealed that spreading the tail on its own had only a subtle effect on the trimmed configuration of the UAV. For example, morphing the tail from a furled to a spread configuration resulted in less than a 0.5° shift in the trim angle of attack when the tail was held at 0° incidence angle. In addition, spreading the tail in this configuration only increased the lift and drag noticeably for angles of attack above 14° [48]. The authors hypothesized that this was due to increased flow disruption caused by the fuselage. Thus, in future UAV designs, tail spreading could be a more effective method of control if fuselage flow separation was minimized [48].

These UAV results agree with biological findings as well. Experimental studies on prepared starlings showed that, even when the body was at an angle of attack of 15°, the tail lift coefficient was not significantly affected by tail spreading alone [228]. Therefore, tail spread actuated at low tail incidence angles likely does not represent an effective means of longitudinal control. Instead, tail spread on bird-scale designs has been found to substantially increase the lift force and pitch control effectiveness of a given tail incidence angle across several angles of attack [48,206,211]. Thus, tail spread in birds may predominately serve to magnify the effectiveness of the other tail degrees of freedom.

As mentioned previously, Ajanic et al. [48] also studied the dynamic characteristics of their UAV. During a pull-up maneuver, the Lishawk demonstrated that, for a given negative incidence angle (upwards deflection, Fig. 8), spreading the tail allowed for faster changes to both the linear and rotational (pitch) accelerations. In effect, a spread tail allowed more maneuverable flight by increasing the pitch speed and reducing the pull-up radius.

The relationship between tail area and longitudinal control and maneuverability on aircraft has been understood for some time. Simplified models of aircraft predict that the pitch authority due to elevator deflection or tail rotation is directly proportional to the tail area [27,230]. The ability to spread a tail and increase the tail area would likely be beneficial to birds while completing a maneuver such as perching. In fact, multiple birds have been observed to increase the tail spread and use a negative incidence angle while extending their wings during landing [14,59,208]. This demonstrates a key component of longitudinal control in birds, coupled wing and tail morphing, which will be discussed further in Section 4.

For a constant wing configuration, tail spread can be used to control the longitudinal static stability characteristics. Spreading the tail increases the overall lift curve slope and the tail volume coefficient, which yields an aftward shift in the neutral point of the aircraft [48,231]. As long as this aftward shift of the neutral point is smaller than any associated aftward shift of the center of gravity, increasing the tail spread will be stabilizing in pitch [28,62,206]. This was the case for the Lishawk [48] and Zheng et al. [211]'s tail design, which confirmed that increasing the tail spread angle tended to increase longitudinal static stability.

3.3.2. Lateral

A symmetrically spread, level tail will predominately affect the longitudinal forces and moments, however there is evidence that birds also actively adjust their tail spread during lateral maneuvers. For example, when entering a banked turn, the steppe eagle used a spread tail configuration and the spread angle was reduced throughout the banking maneuver, similar to the incidence angle [14]. In addition, the tail spread angle was noted to transiently fluctuate, which the authors hypothesized could indicate that tail spread also provides an active control mechanism to damp dynamic oscillations caused by atmospheric turbulence. When combined with other degrees of freedom, tail spread may play a substantially more complex role in lateral flight control than has been studied to date and covered in this review.

3.4. Tail shape

Studies have found that the overall control forces provided by a tail will be substantially affected by its shape, with most studies on tail shape focusing on forked tails, due to their prevalence in nature. Note that the top panel in Fig. 10 is most similar to a “graduated tail” shape but, there is substantial variation in tail shape across bird species including shapes that are more rounded, squared, wedged, etc.

Historically, a forked tail has been associated with higher maneuverability. Balmford et al. [232] studied forked tails on bird specimens and found that birds who feed aerially (and were thus expected to be more maneuverable) were less likely to have a graduated (unforked) tail. Analytical results from delta-wing theory predicted that forked tails enhance maneuverability although tails with a “deeper” fork were less efficient [208,229,232]. However, the results from delta-wing theory have since been brought into question in light of experimental and computational studies that contrasted with theoretical expectations [202,228]. As a result, future work is required to definitively comment on the aerodynamic efficiency provided by a forked tail.

In the following section, we focus on longitudinal effects of the tail shape however, there is evidence that the lateral stability provided by the tail will be affected by the overall shape [210].

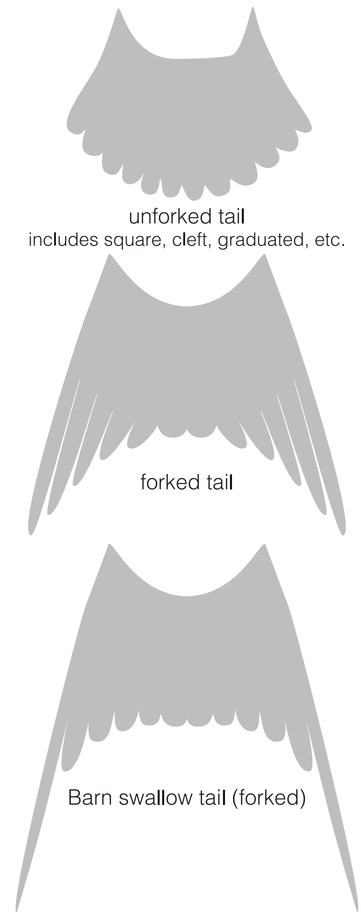

Fig. 10. Simplified renditions of some variations of tail shapes seen in birds.

3.4.1. Longitudinal

Hummel’s experimental studies on engineered tails found that varying the tail shape between a wedged and forked shape (with the same amount of surface area) had a negligible effect on the produced aerodynamic coefficients [206]. This result suggests that the aerodynamic difference between forked and unforked tails in flight are likely a result of differences in tail area. By allowing the tail area to vary, Hummel [206] showed that forked tails were less longitudinally stable than similarly shaped unforked tails and that, as the fork depth increased, the longitudinal stability decreased for a constant spread angle.

Rather than purely a method to decrease longitudinal stability, Hummel instead noted that a potential benefit of forked tails was the rate of change in the longitudinal stability caused by the spread angle [206]. The author found that spreading a forked tail led to a larger rate of increase in longitudinal stability than spreading an unforked tail with the same tail base width. Note that the area of these tails was not equivalent. This increased response of the stability characteristics could possibly indicate enhanced maneuverability for a design with a forked tail as predicted by Thomas [208].

Further indication of enhanced maneuverability is revealed by the reduced longitudinal stability associated with forked tails, as this reduces the amount of control moment required to complete a maneuver. However, Hummel also showed that a forked tail would have reduced pitch control effectiveness compared to unforked tails due to the reduced tail area (for a constant spread angle and base width) [206]. This indicates that a forked tail requires larger tail deflections to produce control moments equivalent to those of an unforked tail. Due to these contrasting results related to the maneuverability of a forked tail, it is not immediately apparent which tail shape should yield the most maneuverable flight. More work is required to determine if the high response rate and lowered stability offered by a forked tail can outweigh the control effectiveness gained from using a larger tail area.

Ornamental tails have also been a focus of avian studies due to their, likely substantial, impact on flight efficiency [229]. Norberg [233] found that barn swallows (*Hirundo rustica*) benefited from the long streamers on either edge of the tail (Fig. 10). The aerodynamic benefit of such a tail configuration was due to feather flexibility, which causes the streamers to “droop” into a concave (downward) shape, thus increasing the curvature along the length and width of the tail when the tail was at a positive incidence angle (Fig. 8). These tail streamers were hypothesized to function similarly to both a Krüger flap and leading-edge vortex flaps, which increase lift generation during turning maneuvers to improve the overall agility of an aircraft [233]. A comparative study confirmed that birds with forked tails had increased flexibility in their outer tail feathers lending credence to this idea [234]. UAV designs could take inspiration from these findings by designing a tail with variable flexibility along its width.

In all, more work is required to identify the advantages and disadvantages of forked tails. Zheng et al. [211]’s tail design uses a forked shape but, currently, there are no data to indicate what specific aerodynamic effects are caused by this unique tail shape for the UAV.

Note that forked tails represent just one type of unique tail morphology [210]. As there is substantial variation in tail ornamentation across avian species, each morphology could benefit from a directed study to identify the aerodynamic effects of these unique tail shapes.

3.5. Tail rotation

The third tail degree of freedom considered in this review is rotation about the x-axis (Fig. 11). Bird tail rotation has been likened to the rudder of a conventional aircraft due to its ability to redirect forces in the y-axis [61]. However, the shape change caused by rotation of the entire tail is substantially different than a rudder and thus, is expected to have a unique function.

3.5.1. Longitudinal

The correlation between tail rotation and changes in longitudinal forces is not well-documented. As a lifting surface, tail rotation can be expected to re-orient the aerodynamic forces so that vertical component (lift) is reduced while the horizontal component (side force) is increased. Parga et al. [212] experimentally found that tail rotation, for positive tail incidence, had a minor negative effect on both lift and drag, regardless of the direction of actuation. The reduction in drag was attributed to a reduction in induced drag. Parga et al. [212]'s result is intuitive, since rotation of the tail would marginally reduce the horizontal lifting area, and hence reduce the lift and induced drag. Similar lift reductions were also found by Gamble and Inman [213], although the bend–twist coupling of their MFC actuators likely contributed to additional lift reduction. Additional research is required to provide a better understanding how (or if) birds use tail rotation in flight for longitudinal control. Meanwhile, the effect of tail rotation on lateral stability and control has been explored in more detail.

3.5.2. Lateral

Even though the lift and drag response were found to be largely independent of the direction of tail rotation, Parga et al. [212] found that the relationship between tail rotation and side force is more complex. The magnitude of the side force was found to increase symmetrically with tail rotation, but the direction of the side force depended on the sign of the lift force acting on the tail. As discussed in Section 3.2, the sign of this lift force will depend both on the tail incidence as well as the tail's overall angle of attack. Fig. 11 depicts the resulting side force produced by the tail according to the direction of lift and rotation of the tail. For example, a positive tail rotation (illustrated in Fig. 1) will generate a positive (rightward) side force when the lift on the tail is positive, but will generate a negative (leftward) side force when the lift on the tail is negative. This coupling between the tail degrees of freedom was confirmed by experimental results from Hummel [206] and flight tests from Hoey [235].

Tail rotation will generate yawing moments, because the side force generated by a bird's tail will always act aft of the center of gravity. As such, the sign of the yawing moment in response to tail rotation is also affected by the sign of the tail lift [206,212] as depicted in Fig. 11. For example, for a positive tail rotation with a positive lift force (upper right-hand corner of Fig. 11), a negative incidence angle would reduce the lift and reduce the existing yawing moment. In contrast, downwards deflection of the tail (positive incidence) would supplement the negative yawing moment. Despite this challenge, Parga et al. [212] found that rotating a V-tail produced yawing moments equivalent to that of a comparable rudder if the tail was at high positive incidence angles. With this configuration, the authors suggested that tail rotation would be effective for yaw control but stressed that substantial control challenges were introduced by the control dependence on the directionality of the tail lift.

Gamble and Inman [213] achieved yaw control on an avian-inspired rudderless design using MFC actuators, although the tail harnessed bend–twist coupling of fiber composites and cannot be characterized as pure tail rotation. Interestingly, the authors found a linear relationship between the yawing moment generated and the tail displacement (a combination of incidence and rotation as described in this work) for the full range of displacements tested. In contrast, a rudderless aircraft design that used a split trailing-edge flap for control exhibited a nonlinear response [236]. The linear trend from Gamble and Inman [213]'s design indicates that this tail would have a constant yaw control effectiveness, which facilitates simple control algorithms and suggests that coupling rotation with tail twisting may be a promising mode of lateral control for rudderless UAVs.

Avian-inspired tail rotation contributes to roll control as well. As with yaw, tail incidence increased or decreased the tail's contribution to the rolling moment depending on the direction of incidence angle [206]. Specifically, according to Hummel [206], a positive tail rotation angle (Fig. 11) produced a negative rolling moment, which would be supplemented (made more negative) by a positive tail incidence angle and counteracted (made more positive) by a negative tail incidence angle. Similar to the yaw control, these coupled relationships complicate the control laws required to effectively fly the aircraft. Hummel's findings were later confirmed by Parga et al. [212]; however, the authors noted that their roll coefficient was much smaller than that of traditional ailerons. This reduced effectiveness indicates that tail rotation may not be used as a primary form of roll control in birds. The physical phenomenon enabling tail rotation to generate rolling moments requires future research.

Tail rotation may also be used for specific lateral maneuvers. For example, Thomas [208] hypothesized that tail rotations were used to counteract adverse yaw, though observations of pigeons did not find the tail was being used in this manner in slow flight [237]. Of note, Parga et al. [212] found that their rotatable V-tail design likely would demonstrate a proverse yaw response when in a trimmed configuration. In-flight observations of the steppe eagle in a right turn (towards the positive y-axis), Gillies et al. [14] attributed transient negative tail rotations to counteracting adverse yaw.

In addition to controlling adverse yaw, studies have also investigated how tail rotation is used to initiate banked turns. Oehme [71] observed that a hen harrier initiated a banked turn to the right by using a negative tail rotation in combination with wing planform changes. This is consistent with the findings of Hummel [206] and Parga et al. [212]. The authors observed that, in the presence of positive tail lift, negative tail rotation generated positive yawing and rolling moments, both of which would contribute to a nose-right lateral motion. To stop the banked turn, the hen harrier used a rapid positive tail rotation [71]. Similarly, Gillies et al. [14] observed a positive tail rotation in the final stages of the rightward-banked turn of a steppe eagle. These results suggest that a rotating tail may allow rapid initiation of banked turns for an avian-inspired UAV.

Tail rotation will also affect the lateral static stability of a flyer by adding to the surface area in the x-z plane. Hummel [206] found that the roll versus sideslip curves for a tail with 30° rotation was shifted by a constant value, resulting in no change in slope and therefore no change in roll stability. This result indicates that tail rotation may provide effective roll control, although as discussed previously, the overall effectiveness may not rival traditional roll control methods. In contrast, tail rotation produced a large change in yaw stability when compared to a planar tail [206]. A positive tail rotation increased the slope of the yawing-moment versus sideslip curves, thus increasing the overall yaw stability when compared to the planar tail. This is analytically expected as the yaw stability is directly proportional to the vertical tail area, which is increased by tail rotation [29]. Parga et al. [212]'s experiments also confirm that increasing tail rotation increases the static yaw stability. Note that Hummel [206] also found that twisting the tail in either direction reduces the side force with increasing sideslip angles leading to increased yaw stability independent of the direction of rotation. Interestingly, the yaw stability of Gamble and Inman [213]'s MFC design did not increase with tail actuation, likely due to the MFC's bending–twisting coupling.

Little biological research has investigated the effects of tail rotation on lateral stability. Thomas [208] proposed that tail rotation could be used to augment yaw stability, similar to the vertical tail on an aircraft. This expectation agrees with Parga et al. [212]'s and Hummel

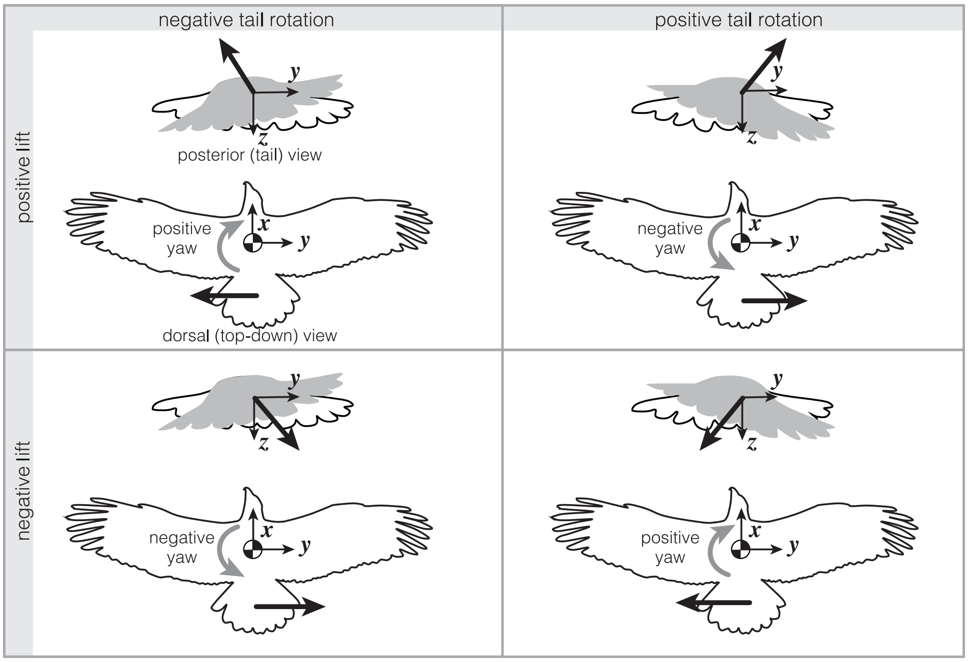

Fig. 11. Depending on the directionality of the lift generation, tail rotation can produce either positive or negative yawing moments.

[206]'s rigid tail results. Furthermore, Gillies et al. [14] observed that for a rightward-banked turn (towards the positive y-axis), the tail exhibited steady positive rotation at the start of the turn which was hypothesized to counteract spiral instability (a lateral dynamic stability mode, refer to Appendix A). As it stands, our understanding of the role of tail rotation in controlling lateral stability in birds requires additional studies.

4. Coupled wing–tail morphing

Throughout this review, we identified studies that have morphed parameters within the tail or within the wing, but there are currently few studies that have performed a detailed investigation of coupled wing-and-tail morphing.

As mentioned in Section 3.3, perching birds will spread their tail, reduce the tail incidence, and extend their wings. Similarly, the lowest pull-up radius, and thus the sharpest turn, achieved by the Lishawk had fully extended wings with a spread tail [48]. This supports theoretical studies on aircraft that predict the stall-limited turning radius is nearly inversely proportional to the wing area [238]. Further, this result matches what is understood about the influence of wing location and tail geometry on maneuverability of traditional aircraft [230]. Additionally, Ajanic et al. [48] found that power could be minimized by morphing to different configurations of tail spread, incidence, and wing sweep across different flight speeds. Further investigation of additional wing and tail morphing degrees of freedom will yield additional insights in the future.

Intriguingly, the Lishawk used forward swept wings (discussed in Section 2.2) with a fully spread tail to obtain a stable trim point at a high angle of attack. If we consider this result collectively with the Lishawk's pull-up maneuvers and Hummel [206]'s results on tail spread, this suggests that birds who regularly use high angles of attack in landing maneuvers may be able to spread their tail to achieve controllable, stable flight at these high angles of attack. In addition, an analytical analysis of a UAV with a morphing wing and tail incidence angles suggested these angles could be optimized to successfully perform an avian-like perching maneuver [60]. Confirming that birds can obtain a stable trim point at high angles of attack will be necessary to confirm this hypothesis.

Live birds regularly adjust both their wings and tails in unison. For example, two raptors were observed to fluctuate the wing's angle of incidence simultaneously with the tail spread during landing maneuvers [14,208]. The birds would hold their wings at a high angle of incidence as the tail was spread and then lower the wing's angle of incidence while furling the tail. Identifying other morphing sequences used by live birds will likely prove useful in inspiring UAVs with coupled wing–tail morphing.

Another critical role of wing–tail coupling will be the implications for the longitudinal static stability of birds. This is because coupled morphing improves the ability of a flyer to shift its neutral point. This is especially relevant in light of evidence that birds glide with a positive lift force on their tail [218]. The possible wing/tail configurations were discussed in detail within Section 3.2. Further research is required to better understand how birds navigate the associated trade-offs in stability and balance.

Details about the positions of the tail and wing can be gained from observational studies. Storer [109] studied the slow gliding flight of the great egret (*Ardea alba*)and observed that as the tail was spread during slow flight, the wings were swept forward. Similarly, Tucker [65] observed that a soaring Harris' hawk *(Parabuteo unicinctus)*, among other species, only spread its tail while the wings were fully spread. Both authors hypothesized that tail spread was used to compensate for the increased pitching moment generated by spreading the wings, which would move the aerodynamic center forward.

Alternatively, it is possible that some bird wing configurations lead to a positive pitching moment about their aerodynamic center (i.e., M_{AC} in the opposite direction than shown in Fig. 9) [31,49,135,141]. If this value is high enough, it may permit trimmed and statically stable flight when the aerodynamic center is behind the center of gravity.

In all, the studies outlined in conjunction with the aerodynamic literature indicate that coupled control will enhance the control moments and stability offered to UAVs in flight and may be a fundamental component of birds' impressive maneuverability and adaptability. It is possible that engineered designs may need to explore new areas to efficiently and effectively control this coupled system, such as leveraging machine learning approaches. There is much additional work required to determine the most beneficial attributes that are provided by coupled wing–tail morphing as well as to realize such a complex control methodology on bird-scale UAVs.

5. Conclusion

Engineers have long been envious of avian flight due to birds' seemingly effortless gliding capabilities, maneuverability, and reconfigurability. To date, few avian-inspired morphing UAVs have been able to achieve true bird-like flight. Understanding the features of bird flight that permit these enviable traits can provide engineers insight that may enhance our capabilities to accomplish a diverse set of missions. In this survey, we compiled and analyzed the aerodynamic control capabilities due to the degrees of freedom in the wing and tail of gliding avian species and avian-inspired UAVs. We also detailed the current state-of-the-art of these engineered designs.

As the principle lifting surface, wing morphing allows for large-scale changes in lift and stability. Wing sweep morphing can tailor the lift in response to changes in flow speed and generate rolling and yawing moments when morphed asymmetrically. Both applications have been documented in birds. Wing sweep also enables direct control over the static margin, allowing the flyer to easily adjust its longitudinal stability characteristics. Furthermore, incorporating additional sweep joints (shoulder, wrist, and finger) enables more complex control capabilities. Asymmetrically morphing the wing dihedral adjusts the side force generated by the wings, controlling yawing moments and enabling coordinated turns. Wing twist locally changes the angle of attack of the wing along the span and when actuated asymmetrically, can be used to control the rolling moment while possibly maximizing the aerodynamic efficiency. Birds are known to adjust their wing twist in flight; however, asymmetric wing twist may be coupled with other degrees of freedom. Finally, research into morphing the wing camber is well-established and has demonstrated global improvements in flight efficiency, capabilities for local tailoring of the wing's lift distribution, and roll control through asymmetric actuation.

Both bird and avian-inspired UAV studies have shown that a controllable tail is important for flight control. Tail incidence is used to generate pitching moments, like elevators on an aircraft, by manipulating the lift force aft of the center of gravity. In birds, tail incidence is frequently adjusted during landing and perching maneuvers as they require strong pitching moments. Tail spread amplifies the tail's generated lift force and the resulting pitching moments by increasing the planform area of the control surface. Notably, both bird and avian-inspired UAV studies observed that tail spread was necessary to trim and provide body weight support during slow gliding flight. Finally, tail rotation redirects the lifting forces on the tail generating both rolling and yawing moments; however, tail rotation presents challenges to designing effective flight controllers as the direction of the resulting roll and yaw moments is dependent upon whether the lift on the tail is positive or negative. Observations of avian tail rotation during banked turn maneuvers have led biologists to hypothesize that tail rotation may be used to supplement rolling moments generated by the wings, counteract adverse yaw, and increase the lateral static yaw stability.

A few key gaps in the literature were evident while conducting this review. Many of these areas are discussed throughout the text, but here we detail some common ideas in the hopes of inspiring new avenues of avian and avian-inspired morphing UAV research. Firstly, much of the previous studies leveraged experimental or computational results due to birds' complex morphology but future work should strive towards formulating analytical expressions that can extend relationships to unobserved flight conditions and/or can capture the variation of attributes within flying birds. This work will serve to advance our theoretical comprehension of avian flight. Next, while much research has been dedicated to birds in steady flow environments, relatively little work has been conducted to understand their control response in dynamic and turbulent environments such as gusts, and how they use large-scale maneuvers, like wing tucks, to mitigate these effects. Such work will provide critical insights on avian flight.

We found that the coupled effects of wing–tail morphing must be further understood in order to maximize maneuverability and performance. We discussed each degree of freedom of flight control for a UAV or bird independently, but we do not expect that a bird or UAV that couples these degrees of freedom will gain control that is equivalent to a sum of each part. Instead coupled effects likely have unique characteristics due to the complexities introduced by the non-planar shapes and associated interaction effects between the different components. Directed work on the overall coupling implications in live birds will be necessary. These studies should in turn be informed by work on how the control authority of morphing is affected by aeroelastic effects.

Although we have discussed flight control through a purely physical evaluation (an aerodynamic output due to a morphing shape change input), there are multiple fields of research dedicated to understanding and implementing the algorithms necessary to effectively control flight. Note that this is not only an ongoing area of study within engineering but there is ongoing work within biology, often focused on vision and sensory inputs [8]. It is highly likely that avian flight control is dependent on distributed sensing and rapid neural processing. As with morphing, there is substantial overlap between the engineering and biological disciplines that warrants collaboration to advance towards a common goal of understanding the control algorithms used in multi-degree of freedom and highly coupled flight systems.

Another outstanding question is if the discussed avian-inspired control mechanisms outperform those implemented by traditional aircraft. This answer requires knowledge of the actuators' control effectiveness and control derivatives, many of which are not quantified by avian-inspired morphing UAVs and biological flight studies. This will be invaluable knowledge moving forward for future studies on the effectiveness of these avian-inspired control methodologies.

Just as traditional aircraft controls will depend on the aircraft design, operating condition, and the desired maneuvers, it is likely that birds' control capabilities depend on similar factors as evidenced in this review. Work is required to identify how differences within and among bird species in avian morphology, environment, and behaviors will impact the resulting flight control capabilities. Further, it is important to recognize that the function of birds' wings and tails includes unique constraints outside of those that govern flight.

Collectively, it is our aim that this review serves to highlight key areas in which avian flight may offer inspiration for future UAVs and identify possible hypotheses from UAV designs that may guide future avian maneuverability studies. We hope that illuminating these gaps in the literature will propel the field of avian-inspired morphing UAVs forward into the next stage of technological readiness for these morphing mechanisms.

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Table 1
Bird and UAV studies that have quantified contributions of wing and tail morphing parameters on key aerodynamic control characteristics.

		Longitudinal control			Lateral control		
		Lift & Drag	Pitch	Stability	Side force	Roll & Yaw	Stability
Wing morphing	Sweep	[10,39,42,45–48,50–56,58,62,68]	[33,39,45,48,51,59,60,62,68]	[39,44,46,48,51,53–58,62–65,68]	–	[33,46–48,50,69,70,73,74]	[44,50,77,79,80]
	Dihedral	[31,39,82,83,85,88–90,103,106,107]	[31,39,101,108]	[7,31,39,70,84,91,103,104,111]	[85–87,90]	[74,78,84–88,95–97,101,102,108]	[14,70,79,81,84,90,96,97,103–105,111]
	Twist	[110,114,116,117,120]	[110,114]	[111]	[87]	[14,69,70,84,111,113,114,116–120]	[111]
	Alula	[123–129,131]	–	–	–	[128]	–
	Camber	[59,133,141,143–145,162,164,170,172,174,179–184,186,191–196,198,199]	[144,181,198]	–	–	[172,181,195–198]	–
Tail morphing	Incidence	[48,67,72,206,208,211–213,216,225]	[48,72,206,208,211]	[206]	[206,212,235]	[206,212,213]	–
	Spread	[11,48,53,54,56,81,205,206,211,216,218,228,229]	[48,206,208,211]	[48,206,211]	–	–	–
	Shape	[206,208,228,229,232]	[206,208,228,229,232]	[206,208,232]	[206,210]	[206,210]	[206,210]
	Rotation	[212,213]	–	–	[206,212,235]	[206,208,212,213]	[206,208,212]
Wing-tail morphing		[48,60]	[48,60]	[48,60]	–	–	–

Table 2
Live gliding bird studies that have used quantitative and/or qualitative analyses to discuss wing and tail morphing parameters on key aerodynamic control characteristics.

		Longitudinal control	Lateral control
Wing morphing	Sweep	[14,53–59,61,64,66,67,70,71,81,109]	[14,70,71]
	Dihedral	[7,14,67,70,81,91]	[14]
	Twist	[14,70,81,91,109]	[14,67,71,109]
	Alula	[59]	–
	Camber	[59,70,81,81,135,141]	–
Tail morphing	Incidence	[14,59,81]	[14]
	Spread	[14,53,54,56,59,67,70,81,109,202,208,229]	[14]
	Shape	[202,229,232,233]	–
	Rotation	–	[14,71,208]
Wing-tail morphing		[14,65,109,208,218]	[14,208]

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Glossary of relevant flight dynamics terminology

As this work is intended to be accessible by both readers in the engineering and biological fields we have included a short overview of the terminology used in the discussion of flight dynamics and control. For further details we refer the reader to textbooks on aerodynamics and flight mechanics [26–29].

Adverse yaw. A phenomenon wherein the generation of rolling moments by the ailerons on the main wing is negatively coupled with the generation of yawing moments by the ailerons.

Aerodynamic center. The point about which the pitching moment of a lifting surface (or aircraft) does not change in response to changes in angle of attack.

Aileron. A control surface on the trailing-edge of the main wings that is primarily responsible for creating rolling moments.

Control effectiveness. A measure of the change in an aerodynamic force or moment produced by the deflection of a control surface. For example, the pitch control effectiveness on a traditional aircraft is defined as the change in pitching moment due to a unit deflection of the elevator.

Dutch Roll mode. A lateral dynamic mode of an aircraft characterized by out-of-phase combination of sideslip, rolling, and yawing oscillations. Affects aircraft controllability.

Elevator. A control surface on the trailing-edge of the horizontal tail.

Flap. A control surface on the main wing. Has many different purposes, but is generally used to manipulate lift generation on the main wing.

Lateral degrees of freedom. Refers to the aerodynamic forces in the y-direction and the aerodynamic moments about the x- and z-axes. Generally given in the wind-fixed (sideforce, C_Y) and body-fixed coordinate systems (rolling moment, C_ℓ, and yawing moment, C_n) respectively.

Longitudinal degrees of freedom. Refers to the aerodynamic forces in the x- and z-directions as well as the aerodynamic moment about the y-axis. Generally given in the wind-fixed (lift, C_L, and drag, C_D) and body-fixed coordinate systems (pitching moment, C_m) respectively.

Morphology. The shape, structure and/or configuration of a flyer.

Neutral point. The point on an aircraft about which the pitching moment does not change with angle of attack. Also referred to as the aerodynamic center of the aircraft.

Rudder. A control surface on the trailing-edge of the vertical tail that is primarily responsible for creating yawing moments.

Spiral mode. A lateral dynamic mode of an aircraft characterized by changes in heading. Affects aircraft controllability.

Static margin. The relative distance between the center of gravity of a aircraft and the neutral point usually expressed as a fraction of the mean aerodynamic chord of the main wing. The static margin is positive when the center of gravity is forward of the neutral point and indicates an aircraft that is statically stable in pitch. Likewise, a negative static margin indicates static pitch instability.

Static stability. The ability for an aircraft to return to a given trim state when perturbed from that state. Note that static stability is a necessary but insufficient condition for fully stable flight. Full stability also requires a stable response over time (dynamic stability).

Static pitch stability. An aircraft is statically stable in pitch when a positive change in angle of attack produces a negative (nose-down) pitching moment. Symbolically given as:

$$\frac{\partial C_m}{\partial \alpha} < 0. \quad (1)$$

Static roll stability. An aircraft is statically stable in roll when a positive change in sideslip angle produces a negative (right wing-up) rolling moment. Symbolically given as:

$$\frac{\partial C_\ell}{\partial \beta} < 0. \quad (2)$$

Static yaw stability. An aircraft is statically stable in yaw when a positive change in sideslip angle produces a positive (nose-right) yawing moment. Symbolically given as:

$$\frac{\partial C_n}{\partial \beta} > 0. \quad (3)$$

Tail volume coefficient. The product of the tail area and distance from the center of gravity to the aerodynamic center of the tail. Increasing this product always increases the pitch stability of an aircraft. (V_H), which is defined as: $V_H = \frac{l_t S_t}{S_w c}$, where l_t is the distance between the center of gravity of the body in flight and the aerodynamic center of the tail, S_t is the horizontal tail area, S_w is the wing area, and c is a longitudinal reference length.

Trim. A state of equilibrium in aircraft where the aerodynamic forces and moments acting on the aircraft balance the forces and moments created by the weight, rotation rates, and inertia of the aircraft.

Appendix B. Overview of morphing parameters and control effects

See Tables 1 and 2.

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