

Review

Bioinspiration review of Aquatic Unmanned Aerial Vehicle (AquaUAV)

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ABSTRACT

The performance of Aquatic Unmanned Aerial Vehicle (AquaUAV) has always been limited so far and far from practical applications, due to insufficient propulsion, large-resistance structure etc. Aerial-aquatic amphibians in nature may facilitate the development of AquaUAV since their excellent amphibious locomotion capabilities evolved under long-term natural selection. This article will take four typical aerial-aquatic amphibians as representatives, i.e., gannet, cormorant, flying fish and flying squid. We summarized the multi-mode locomotion process of common aerial-aquatic amphibians and the evolutionary trade-offs they have made to adapt to amphibious environments. The four typical propulsion mechanisms were investigated, which may further inspire the propulsion design of the AquaUAV. And their morphological models could guide the layout optimization. Finally, we reviewed the state of art in AquaUAV to validate the potential value of our bioinspiration, and discussed the future prospects.

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1. Introduction

Aquatic Unmanned Aerial Vehicle (AquaUAV) travel freely between water and air, which was proposed by [1]. It dives underwater quickly from the air to avoid tracking, and launch itself from underwater to pursue enemies [2]. AquaUAV have great potential applications in military and civilian fields and have been widely studied [3–5]. The AquaUAV can be equipped with cameras and sensors for a range of maritime applications, such as plant and animal monitoring, water quality testing and more [4]. However, AquaUAV still has flaws waiting to be solved. For example, the thruster cannot provide enough thrust to achieve continuous and fast locomotion between water and air [6]. The variable structure wing will destroy the streamline design of the prototypes although it can protect the main body from being broken when entering water. And bioinspired AquaUAV are difficult to achieve precisely controlled locomotion such as turning, climbing and emergency diving.

Animals have evolved a range of excellent morphological structures and locomotion patterns through long-time natural selection [7]. These evolutionary advantages may bring some

inspirations for the design and optimization of human technology [8,9]. Among them, some amphibians including but not limited to gannets, cormorants, flying fish, and flying squid can freely travel between water and air (see Fig. 1) [10]. Here, we take these four aerial-aquatic amphibians as typical representatives to review their bioinspiration for the development of AquaUAV. They have made different evolutionary trade-offs in body structure and locomotion patterns to adapt to the vast differences between water and air, evolving variable structural features, which will be discussed in Section 2. Then, their amphibious propulsion mechanism will be summarized (Section 3). Finally, to validate the value of bioinspiration, we will review some existing bioinspired AquaUAV in terms of morphological parameters, variable structure design and propulsion system.

2. Multi-mode locomotion trade-offs of aerial-aquatic amphibians

2.1. Locomotion of aerial organisms

Flight-based amphibians spend most of their time moving above the water surface (including air flight, floating on the water surface, or walking on land), and dive underwater when they need to feed. Gannets and cormorants are typical representatives.

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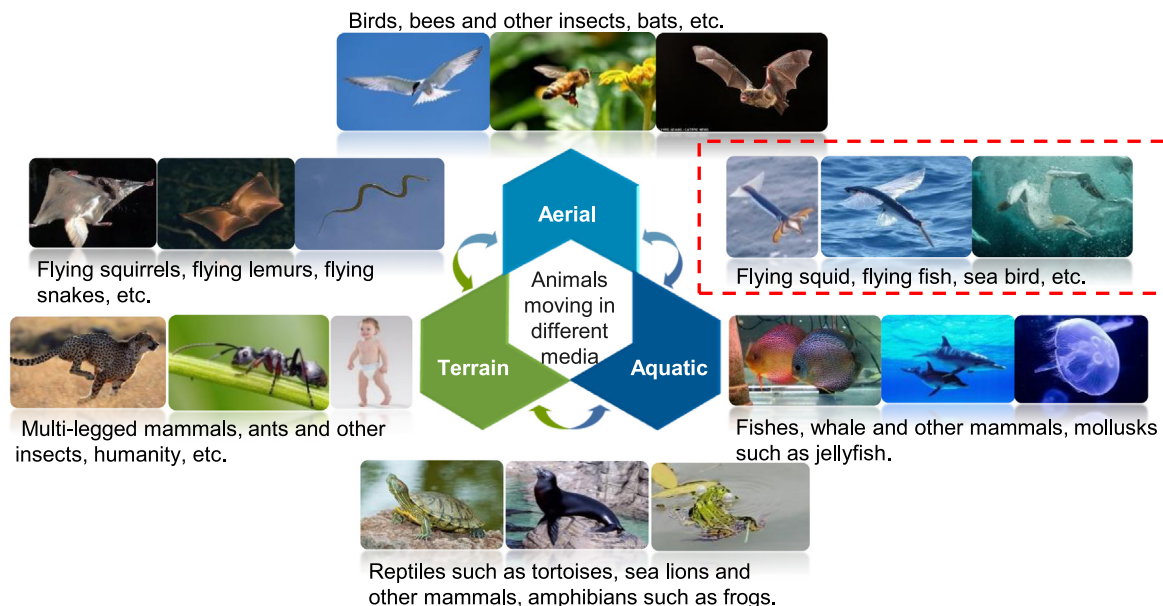


Fig. 1. Some animals move only underwater, in the air or on the land, and amphibians move between two of these domains. Flying squid, Copyright©2013, IOP Publishing (Kouta Muramatsu). Flying fish, Copyright©, BBC. Others, Copyright©, Birdfans.

2.1.1. Gannet

The gannets develop their plunge-diving ability to the extreme [11]. When gannets hover in the sky and then find their prey [12–14], they will launch themselves through the potential energy of gravity, folding wings, and coordinating necks, feet, and tails for trajectory control [15]. They act like arrows striking against the water and seize their prey underwater precisely [16]. Fig. 2 (left) shows the five phases of gannet foraging. Phase 1, the gannet maintains an efficient hovering state, relying on high aspect ratio wings to effectively use the lift of the wind [17]. When finding preys, the gannet adjusts its height and posture using wings, and adjusts the entry angle using feet and tail [15]. They press back Wings against body, folding entire body into arrow shape to minimize the entry resistance [18]. There are also numerous airbag-like structures on their head, neck, shoulders, soles, and almost all its bones [15], which act as protective cushion [19] to prevent from injury during rapid impacts. After entering the water, their body still maintain streamlined arrow shape [16], and penetrate deeper relying on the initial velocity [12,13]. For some tempting prey in deeper water, gannets enter phase 3 and use morphing wing flapping and slight sliding off their feet for secondary acceleration, which helps gannet dive to up to 24 m depth [20]. Phase 4, the gannet quickly rise to the water surface due to the buoyancy provided by air-filled and hydrophobic feathers [21], and the propulsion provided by the flippers tapping and the regularly intermittent body oscillation [20]. After reaching the surface and waiting for the wind to calm down [22], the gannet will spread and swing its powerful wings to glide, continuously beat the water to replenish the thrust using the flippers, and finally achieve a successful surface takeoff [7,10].

2.1.2. Cormorant

Unlike the gannets that plunge-diving into the water from the air, cormorants spend most of their time swimming on the water surface, and diving into the water to hunt only when encountering suitable prey. Their wingspan is only 1.5 times their body length [23] and belong to relatively low aspect ratio, which provide them with excellent flexibility but have difficulties in taking off out of the water [24]. Fig. 2 (right) shows the four phases

of their aerial-aquatic locomotion process. Phase 1, cormorants float on the water surface using their feet to move forward by regularly alternate flapping. When finding prey underwater, the cormorants will gently jump up, bend their body in a certain arc, and then dive into the water [7], which does not pose any risk of damage to the body. Phase 2, the cormorants fold their wings and get thrust through the synchronized flapping of the wide flippers [25] in an intermittent oscillating-gliding mode [26,27], which greatly increases the efficiency of oxygen and energy utilization. Cormorants can dive up to 20 m depth for feeding, more than 100 s dive time [28]. Phase 3, after feeding, the swinging flippers push cormorants up to the water surface. And when reaching the surface, cormorants spread their wings and beat at about 7.5 Hz frequency. Such frequency not only brings them the minimum take-off distance but also reduces the body weight by slapping off the water penetrated in the feathers. The cormorant maintains about 10° attack angle during takeoff, and continuously beat the water surface to achieve a gliding takeoff using their broad flippers [29].

2.1.3. Evolutionary trade-offs summary

Flight-based amphibians were mostly aerial organisms in the early stages of evolution. They made some evolutionary trade-offs as follow to have the ability to dive underwater.

- (1) The characteristics of wings suitable for efficient flight create obstacles to underwater swimming, so the wing size of amphibious birds is gradually reducing. Aerial organisms represented by common guillemot use morphing wings for both swimming and flying, which results higher flight costs than other amphibious seabirds. Aerial organisms represented by cormorants use their flippers for underwater propulsion, which results in higher swimming costs than other amphibious seabirds. When aerial organisms choose to sacrifice their flight ability to reduce the swimming cost, the wing size decreases. Smaller wing increase the wing loading of amphibious seabirds, and they can fly faster. The wing structures for some of them eventually evolve to be thicker and smaller, e.g., penguins.

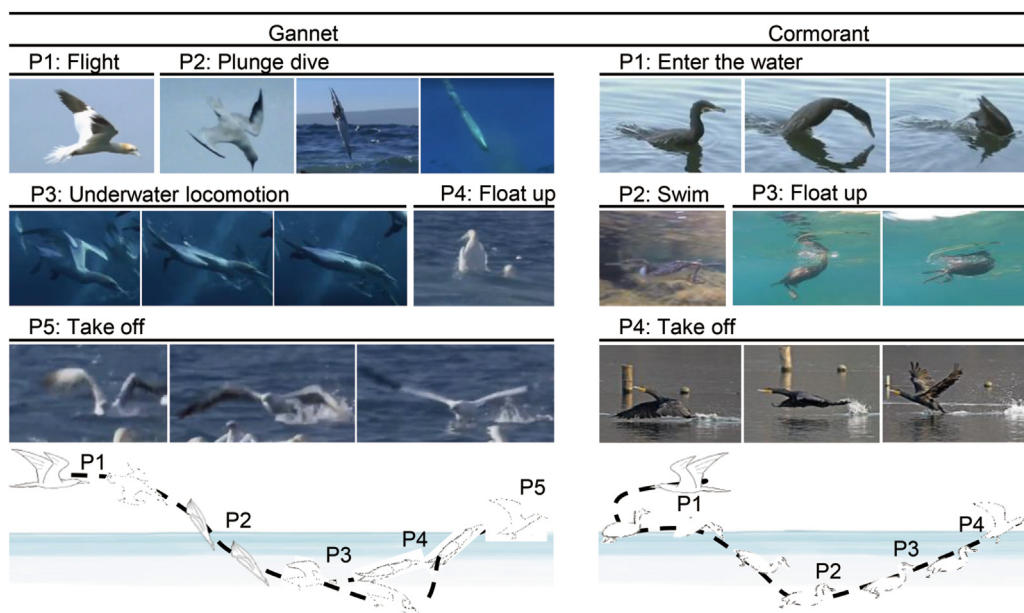


Fig. 2. The aerial-aquatic multi-mode locomotion process of aerial organisms, such as gannet (left), Copyright©2014, BBC, and cormorant (right), Copyright©, Birdfans. P means phase.

- (2) Adaptive changes in the skeleton and muscles of aerial organisms help them adapt to underwater swimming. Aerial organisms with flight ability always have light and hollow skeletons, which make them less difficult to fly. However, such skeletons cause excessive buoyancy when swimming underwater. Therefore, some of them choose to increase the density and mass of their muscles to increase overall weight, making it easier to swim.
- (3) Amphibious seabirds are good at using the air stored in bodies. Birds have special air sacs to help them lose weight. This structure is beneficial for flight but creates excessive buoyancy when diving underwater. Therefore, amphibious birds expel large amounts of gas stored in their feathers, air sacs and lungs before entering the water, but they increase the amount of oxygen in their blood to dive underwater.

2.2. Locomotion of aquatic organisms

Swimming-based amphibians spend most of their time swimming underwater. They will fly out of the water and glide through the air when they need to escape from predators or hurry. Flying fish and flying squid are typical representatives.

2.2.1. Flying fish

Flying fish are excellent evaders that launch themselves into the air to effectively evade predators from underwater [30]. Fig. 3 (left) shows the four phases of their aerial-aquatic locomotion. Phase 1, the flying fish mainly get thrust by swing caudal fin and control the direction by the lateral fins. When entering phase 2, their powerful and complex muscles will contract regularly, driving the caudal fin to swing faster [31]. Their forked caudal fin provides greater thrust than normal fish because the lower lobe is longer than the upper lobe [23]. The flying fish shoot themselves directly into the air at about 20° exit angle [32]. Phase 3, the high aspect ratio pectoral fins unfold [33,34], providing the flying fish with wing loads comparable to cormorants and pelicans [30]. And the flexible pectoral fins can oscillate to control its attitude by feeling the wind direction as it glides through the air [33,35]. Their maximum lift coefficient is at 30° to 35° and maximum lift-to-drag ratio is at -5° to 0° [36]. By utilizing the stall of

the wing [32], the flying fish can turn on flight as well as land quickly [37]. When the body just touches the water surface, the flying fish can enter the second way of phase 2: the flying fish keeps the ventral lobe on the caudal fin in a submerged state at the surface [31,38], and the hyperbatic tail slaps the water at 35 Hz [39]. Therefore, they will glide about 9 m [40] and when the velocity reaches about 10–20 m/s [31], flying fish will extend pelvic fins, lift their tails, and successfully shoots out of the water. They can fly more than 400 m in 30 s using this way [30,34,41].

2.2.2. Flying squid

Flying squid is one of the fastest swimming organisms in the ocean [42]. They have different methods to get propulsion, such as the contracted water-jet by the mantle cavity [43], the swing of flexible carpal fin, and the high-speed fluctuations of the paired fins [44,45]. Such multi-pattern propulsion greatly improves their survival [46]. Moreover, the squid can greatly conserve energy by flying.

Fig. 3 (right) shows the aerial-aquatic locomotion of flying squid. Phase 1, when cruising below 0.2 m/s speed, flying squids rely only on fluctuations of the paired fins to generate power [47]. When slight acceleration is required, the flying squids will inhale small amount of water inside the mantle cavity and eject it [48]. Phase 2, the mantle cavity fully absorbs water and ejects it through the nozzle under the strong contraction of the circular sphincter [47]. The carpal fins of flying squid are folded towards the head, and the long diamond-shaped paired fins are folded over the body, which form the whole body a complete fusiform shape. The flying squid then launches out of the water with the tail forward and the head backward [49]. During water-jet propulsion, the attack angle of tail nozzle is about -3° [47], which reduce the pitching moment. Phase 3, flying squid start the aerial jet propulsion: the paired fins and the carpal fins unfold to the sides, and the mantle cavity squeeze water backward to generate propulsion [50]. Phase 4, when the water has been ejected out, they begin gliding flight through the lift form the unfolded paired fins and carpal fins, and control the flight attitude using the carpal fins [51]. The maximum flight speed reach 11.2 m/s and the maximum flight distance reach 34.5 m [52]. Phase 4, after gliding, the flying squid retracts paired fins and carpal fins and plunge dive into the water [53].

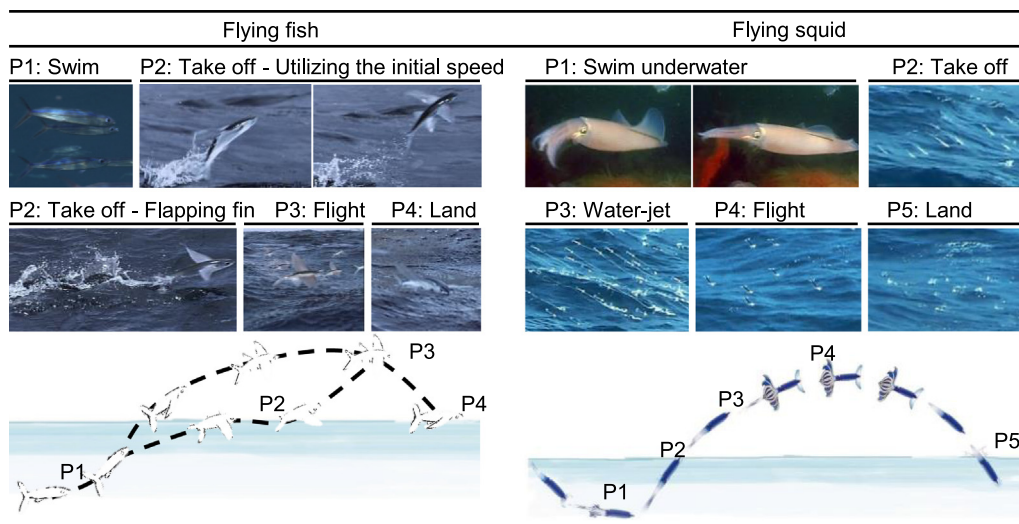


Fig. 3. The aquatic-aerial multi-mode locomotion process of aquatic organisms, such as flying fish (left), Copyright©2011, BBC, and flying squid (right), Copyright©, Prof. Hiroshi Ohizumi from Tokai University.

2.2.3. Evolutionary trade-offs summary

Swimming-based aquatic-aerial amphibians were mostly aquatic organisms in the early stage of evolution. They made some evolutionary trade-offs as follow to have the ability to glide through the air.

- (1) To accommodate aerial gliding, the pectoral and pelvic fins of some fishes (e.g., *Cypselurus*) are enlarged and become elongated to increase flight lift. Therefore, they cannot provide much thrust underwater. The caudal fins of flying fish are also enlarged, and the lower lobe is longer than the upper lobe. Flying fish swim faster through this special fin structure, accelerating to large enough initial speed to fly out of the water.
- (2) Their body become flattened to increase the area of lift generation, e.g., flying fish and flying squid. This increases the area of total lift production when gliding. They can fly longer and farther.
- (3) Greater wing loading and lift-to-drag ratio. The body density of aquatic organisms must be close to water to maintain buoyancy stability underwater. The body mass of flying fish and flying squid is greater than that of aerial organisms of the same size. That causes these aquatic organisms have greater wing loading and lift-to-drag ratios when flying, and also makes them more suitable for high speed flight, allowing them to shoot out from underwater at high speed with large attack angle.

3. Propulsion mechanism of aerial-aquatic amphibians

3.1. Multi-mode propulsion mechanism of aerial organisms

Flight-based amphibians have two main propulsion modes when diving underwater, morphing wing propulsion and flipper tapping propulsion. Aerial organisms either use one of two modes or combine the two modes for propulsion together.

3.1.1. Morphing wings

Some aerial organisms like the gannet, the common guillemot, and alcidæ possess morphing wings that can beat to generate propulsion in both air and water. During diving, morphing wings are partially folded and the hand wings face backward. The joint between the radius-ulna and the hand bones guides

the movement and the wingtips follow, resulting in the wings undergoing a swinging motion [54]. The wings are pronated at the beginning of the downstroke, whereas supinated at the end of the downstroke and the beginning of the upstroke. During the downstroke, the bird accelerates upward and forward [54]. The thrust generated by the upstroke is always greater than that generated by the downstroke due to the need to counteract the high positive buoyancy near the surface [55]. The partially folded wings act as effective swept-back wingtips, which have been shown to reduce induced drag and increase the lift-to-drag ratio during flight [56,57], leading to greater forward force [58,59]. Under unsteady conditions, the swept-back wing of morphing wing underwater shows some superiority in reducing the lift loss at the approach angle that leads to flow separation [60,61]. Compared to other seabirds with same mass, the wing span and wing area of amphibious seabird are reduced, but the span-to-chord ratio remains almost unchanged [62], which increase the gliding and flapping speed [63].

Amphibious seabirds beat at much higher frequency in air than in water, with 8.7 Hz in air but only 1.9 to 2.8 Hz in water [64]. The higher the resistance in water, the slower the muscle contraction rate [65,66]. With nearly constant contraction speed or work done per stroke, the morphing wing vary stroke duration, relative thrust of downstroke to upstroke, and glide duration to regulate swimming speeds [67].

3.1.2. Flipper tapping

Tapping flippers on the surface to take off [29], and regularly swinging flippers underwater to propel [7] are the propulsion methods of amphibious seabirds like cormorants. The “totipalmate” webbed feet [68] and moistenable feathers [69,70] are powerful helpers for cormorants to traverse between water and air, which effectively control and utilize buoyancy. Cormorants sweep their feet along the arch and advance through the water [71]. The arch extends from anterior point along the body main axis to posterior point below the tail. The symmetrical lateral motion of the feet counteracts the lateral forces [26]. The tail moves separately from the rest of the body, controls the pitch moment, and plays an important role in counteracting buoyancy forces. The thrust of the flippers is based on hydrodynamic lift propulsion [72,73] and is the most dominant thrust during the takeoff phase, which exceeds 95% of full thrust [74]. Next one is the buoyancy generated by the body, and the wing-flapping force

Table 1
The propulsion mechanism of typical aerial-aquatic amphibians.

Propulsion	Organisms	Locomotion process	Velocity
Morphing wings	Gannet	A: wings with high aspect ratio and feathers that can utilize the wind	12.2 m/s to 15.6 m/s
		A-S: dash from the sky at an appropriate angle with arrow-like water-entry shape	27.7 m/s
		S: momentum of initial velocity and multi-mode flapping of wings	1.02 m/s to 26.8 m/s
Flipper tapping	Cormorant	S-A: slide by flapping wings, flippers beat the water continuously	-
		A: wings with relatively low aspect ratio and feathered	17 m/s
		A-S: leaping in an arc and plunging into the water from the surface	1.23 m/s
Fin propulsion	Flying fish	S: foot propulsion with wings folded, intermittent kicking/gliding	0.95 m/s
		S-A: slide by flapping wings, flippers slap the water continuously	-
		A: oversized pectoral fins provide large wing loading	10 m/s to 20 m/s
Jet propulsion	Flying squid	A-S: dropping into the water directly	10 m/s
		S: the tail fin swings to generate thrust	-
		S-A: accelerated swing of hypobaric tail, raising pectoral fins	more than 15 m/s
		A: expanded soft paired and carpal fins provide lift	8.38 m/s to 11.2 m/s
		A-S: descend at high speed and retracting the soft paired and carpal fins	-
		S: soft and flexible carpal fin swing, high-speed fluctuation of paired fin	0.2 m/s
		S-A: water-jet propulsion, retracting paired and cardal fins to reduce resistance	6.76 m/s

Note: In this table, A means air flight, A-S means air flight to submerge, S means submerge, S-A means submerge to air flight.

is little. During surface takeoff, the cormorant will tilt at a negative attack angle, generating downward hydrodynamic forces to counteract the upward drift caused by positive buoyancy [26].

Huang et al. suggested that the flipper movements could be classified as flapping and undulating [75]. Dong et al. found that the higher the frequency of the flapping wings, the shorter the distance during takeoff process [29]. When the cormorant takes off with a large angle, the vertical lift becomes larger and the takeoff distance becomes shorter. And the larger the flippers area, the smaller the take-off distance. In addition, the upstream surface of the webbed feet varies with their toe and ventral plate deformation during strokes [76]. During recovery strokes, the webbed feet are folded up to cause relatively low drag when paddling across the water with minimal waterward area. At the end of recovery, the folded flippers are unfolded, thus providing the maximum paddling area for the next stroke. The webfoot is flexible and deforms as propelling the water [77].

3.1.3. Propulsion inspiration summary

The morphing wing is used by aerial organisms like gannet for propulsion underwater, and the flipper tapping is used by aerial organisms like cormorant (see Fig. 4 and Table 1).

- (1) The morphing wing requires changes in the wing size and motion pattern of the aerial organisms. Seabirds wave their wings in a different pattern underwater than when they are in the air, due to the greater drag they face underwater. This is mainly reflected in the frequency of flapping and the manner of tapping.
- (2) The flapping of the flippers requires the cooperation of other body structures to complete the movement. When cormorant pursues its prey underwater, the regular flipper flapping provides propulsive force. Together with the twisting of the body and the driving of the head, the cormorant achieve flexible turns and accelerations underwater.
- (3) The propulsion using both morphing wings and flipper tapping is a trade-off. Flipper tapping provides the main propulsion, while morphing wing flapping provides main turning movements. This reduces the burden of wing movement during underwater flapping, and fully utilizing the propulsive effect of the flippers.

3.2. Multi-mode propulsion mechanism of aquatic organisms

Swimming-based amphibians have two types of propulsion when launching into the air, water jet propulsion and flapping

fin propulsion. Water jet propulsion is mainly the propulsion method of cephalopod mollusks such as flying squid, and flapping fin is mainly the propulsion method of fishes.

3.2.1. Flapping fins

Flapping fins include Body/Caudal Fin (BCF) propulsion model and Median/Paired Fin (MPF) propulsion model [79]. MPF propulsion model is used by fishes like Manta rays [80–82]. BCF propulsion model is used by flying fish. They swing stiff and asymmetrical fat caudal fins to generate enough thrust to break out of the water [23]. The long and narrow wings allow flying fish to glide through the air with loads comparable to those of birds and bats [30,83].

Flying fish generate thrust by generating curved propulsive waves through the body, and by using the caudal fin as an oscillating wing [84–86]. It maintains most of its body rigidity and swims efficiently by tilting its caudal fin in an oscillating manner, using it as a lifting surface and for vortex control. In the four-finned Cypselurus, the flat, broad pelvic fins act as a stabilizer of the center of gravity [30]. The increase in pectoral fin length correlates positively with body length to some extent, but the pectoral fin area decreases relatively, such that the morphology is suitable for fast flight with high lift and low drag [83]. An increase in wing aspect ratio is also associated with an increase in lift-to-drag ratio [87], which reduces the sink speed of the flying fish in the air [88]. Flying fish controls aerodynamic forces by adjusting the dihedral angle [30,34] and attack angle of the pectoral fins during gliding [40] to improve the gliding performance [36]. The aerodynamic body of flying fish [30] and the high lift-to-drag ratio morphology of pectoral fins [36] makes its aerodynamic performance similar to that of birds in gliding flight.

In addition, some fish use fin propulsion to achieve the C-start phenomenon, which is an escape reflex for fish. Fish bend their long, slender bodies into the letter “C” to move towards the surface of the water when pursued by predators [89]. For example, the butterflyfish jump out of the water by bending their bodies [90]. Using the C-start method to jump out of the water, fish will then quickly fall into the water, rather than gliding in the air.

3.2.2. Jet propulsion

The jet propulsion of Cephalopod like flying squid provide instantaneous bursts of force to generate large accelerations, especially during predation and escape [91–93]. The water inside the mantle cavity is pressurized by circumferential contraction of the muscles, and then be ejected from the nozzle [94], forming the vortex ring structure [95].

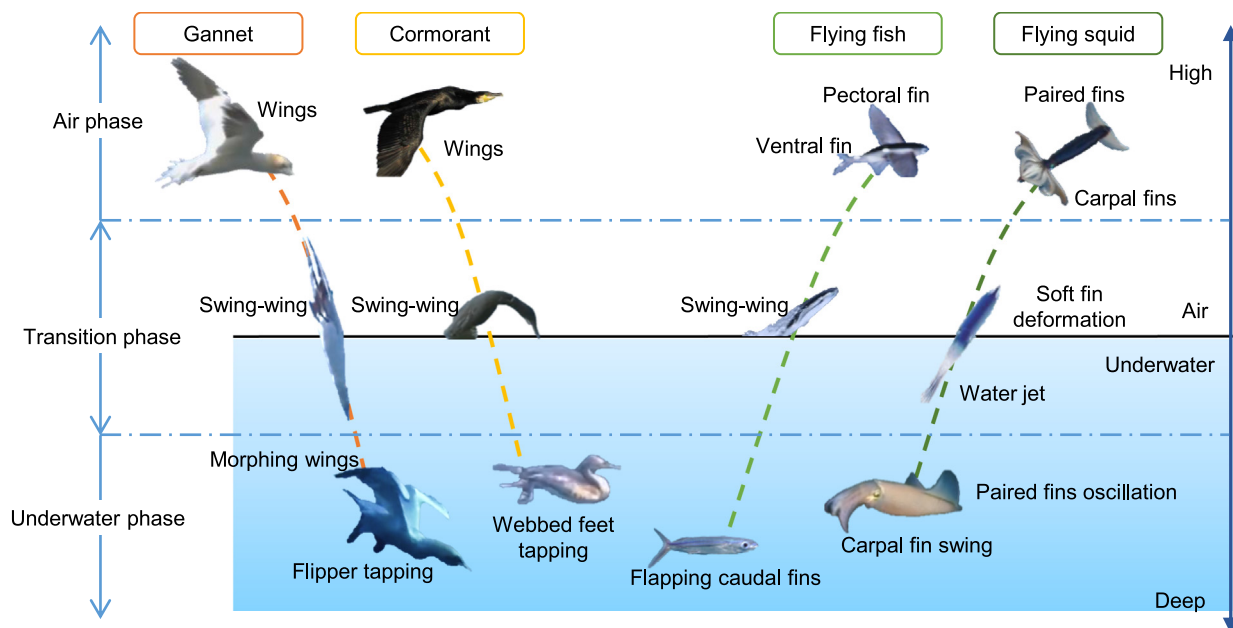


Fig. 4. Power sources of propulsion for aerial-aquatic amphibians in different environments. Take four amphibians of gannet, cormorant, flying fish and flying squid as examples. Gannet (Copyright©2014, BBC), cormorant (Copyright©, Birdfans), flying fish (Copyright©2011, BBC), and flying squid ([78], Copyright©2019, IEEE and Copyright©, Prof. Hiroshi Ohizumi from Tokai University).

Weihls et al. demonstrated that water-jet propulsion can be rationally regulated by a vortex ring mechanism to produce significant hydrodynamic benefits [96]. Anderson et al. derived theoretically that the jet propulsion efficiency equation is inconsistent with the Froude efficiency equation and similar to the propulsion efficiency equation for rocket engines [94]. Gharib et al. found that the formation of vortex rings depended on the ratio L/D , the piston stroke L to the nozzle inner diameter D [97]. Jiang et al. [98] obtained the flow field variation of the jet process in the presence of background flow and concluded that the L/D value of the generated single-loop structure decreases when the background flow is enhanced [99,100]. Anderson et al. hold that the ratio of the background flow velocity to the jet velocity is more important for the flow field structure than the value of L/D , while the propulsion efficiency is found to be higher at higher swimming speeds compared to the value of L/D [101]. Bartol et al. investigated the vortex structure generated by flying squid jet propulsion using the digital particle image velocimetry (DPIV) technique with background flow removed, and they found a total of two distinct flow field structures: a single ring structure and a leading ring followed by a series of accompanying rings, confirming the existence of short-pulse and long-pulse water jet propulsion strategies for flying squid underwater propulsion [102].

3.2.3. Propulsion inspiration summary

The water jet is used by aquatic organisms like flying squid for propulsion to break out of the water, and the fin flapping is used by aquatic organisms like flying fish (see Fig. 4 and Table 1).

- (1) The amphibious propulsion of flapping fins requires the increase of the area of the caudal fin and its surrounding muscles. The enlargement of the caudal fin helps the flying fish to obtain great propulsive force when swinging the caudal fin, which allows the flying fish to gain enough initial speed to break out of the water. In addition, the flying fish use the caudal fin to swing at the water surface to achieve secondary acceleration for takeoff.
- (2) Water jet propulsion requires aquatic organisms to have water storage structure as well as muscles to squeeze the

water. The flying squid inhales water underwater using mantle cavity. When it is time to shoot into the air, the muscles around the mantle squeeze the water and shoot it out through the nozzle. The reaction force of the jet propels the flying squid forward.

4. Aquatic unmanned aerial vehicle (AquaUAV) inspired by aerial-aquatic amphibians

4.1. Morphological design

Aerial-aquatic amphibians often faced with sudden changes in drag and impact forces during air-water transition process. The morphological structures of those organisms have evolved uniquely to protect their body structures, reduce impact forces and improve the efficiency of transition between air and water. Their structural characteristics and morphological parameters can guide the shape design of AquaUAV prototypes (see Fig. 5 and Table 2).

4.1.1. Gannet

The excellent plunge-diving ability of the gannets is due to their special body structure adapting to the multi-mode movement in water and air. The adult northern gannet was chosen as the prototype and the body geometry parameters investigated by [103,104] were collected to build a morphological model of the gannet (see Fig. 5(a) and Table 2). Gannets have the relatively largest body weight, body length, wingspan and body thickness of the four species. While the large wing span reduces maneuverability during flight, it provides more stable and sufficient lift. Many prototypes have adopted such large wingspan design to improve the flight performance in the air [105–107].

4.1.2. Cormorant

Dong et al. took three adult cormorants provided by fishermen and measured the mean values of body parameters of three cormorants (see Fig. 5(b) and Table 2) [29]. Their flipper propulsion helps them to quickly pursue fish underwater.

Table 2
Physical geometric parameters of gannet, cormorant, flying fish and flying squid.

Organism	Gannet	Cormorant	Flying fish	Flying squid
Species	Northern	Phalacrocoracidae	Cypsilurus	Sthenoteuthis oualaniensis
Body mass G (kg)	2.9	2.8	0.06	0.131
Body thickness D_t	80	-	-	30
Total length l_t (mm)	950	840	205	222
Wing span S (mm)	1780	1450	252	120
Wing area A (mm ²)	-	2.49×10^5	7069	-
Aspect ratio $AR = S^2/A$	-	8.45	9	-
Other special	$l_1 = 178$ mm, $l_2 = 210$ mm	$S_{feet} = 118$ cm ²	$A_1 = 1603$ mm ² , $C = 28$ mm	$D_0 = 4$ mm, $l_m = 148$ mm

In this table, l_1 means head length, l_2 means neck length, A_1 means wing area of pelvic fins, C means average wing chord length, S_{feet} means feet area, D_0 means diameter of tail nozzle, l_m means mantle cavity length.

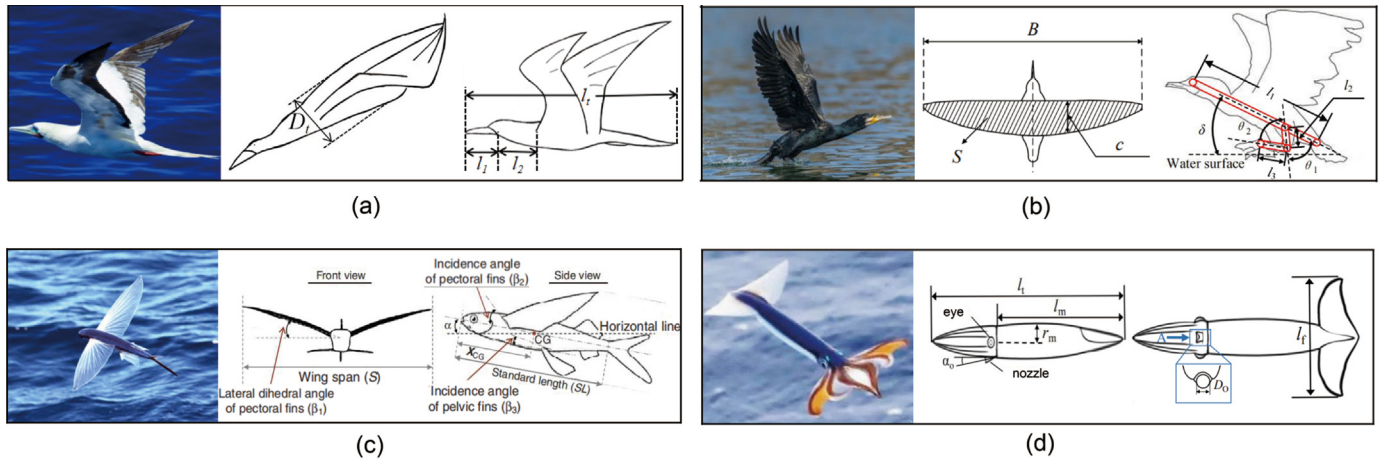


Fig. 5. Morphological theory modeling. (a) Gannet, Copyright©, Birdfans. (b) Cormorant [29], Copyright©2017, IEEE. (c) Flying fish [60], Copyright©1991, AIAA, and Copyright©, BBC. (d) Flying squid [108], Copyright©2019, IOP Publishing, and Copyright©2013, IOP Publishing (Kouta Muramatsu).

There is still a lack of prototypes developed based on the cormorant, and most of the existing work focuses on theoretical and simulation analysis of the flipper propulsion [74,77,109]. The cormorant flipper propulsion might open new paths for the propulsion methods of unmanned underwater vehicle (UUV). The intermittent oscillating-sliding method allows the prototype to maximize energy utilization underwater.

4.1.3. Flying fish

Flying fish take off continuously on the water surface without falling back into the water, and use their wings to change their attitude in the air [83], due to an excellent set of body structures and proportions. Park et al. obtained the geometric parameters of the body of adult flying fishes (see Fig. 5(c) and Table 2) [36]. The caudal fin of flying fish is forked, with the lower lobe longer than the upper lobe. Such special layout provides the flying fish great propulsive force both underwater and in the air. This suggests a way to optimize the caudal fin design for conventional bionic fish robots for larger propulsion.

4.1.4. Flying squid

The theoretical model and the main morphological parameters of Sthenoteuthis oualaniensis are in Fig. 5(d) and Table 2 [108]. The water jet propulsion may provide inspiration for new propulsion methods for both underwater robots and ships. The proportion and size of their body and the mantle cavity may guide the design of new AquaUAV powered by water jet propulsion [110, 111], in terms of size, layout and volume of the water tank. The paired fins and carpal fins can guide the shape, size, and layout design of the bionic wing.

4.2. Variable structure design

Aerial-aquatic amphibians develop variable structures to reduce shuttle drag when traveling between water and air. Gannets, cormorants and flying fish use variable swing-wing. The flying squid uses soft fin deformation. Inspired by the multi-mode structure of those amphibians, AquaUAV prototype also developed the two similar variable structure approaches for transition between water and air.

4.2.1. Swing-wing structure

Gannet folds its wings back as it plunges from the air into the water. The body shoots into the water like an arrow. Such strategy reduces the drag on the body when entering the water and reduce the possibility of injury. Fabian et al. designed the gannet prototype to dive into the water at 7 m/s, with wings fold backward in 0.25 s (Fig. 6(a)) [112]. Liang and Yang et al. conducted a series of studies on the plunge of gannet and bionic prototypes into the water [105–107,118–120] (Fig. 6(b)). They used a high-pressure gas-driven cylinder to fold the wing backward. Together with computational fluid dynamics simulations and physical experiments, their work validates the advantages of the swing-wing structure during the water entry of the gannet.

The swing-wing structure help the AquaUAV make smooth aerial-aquatic transition, which is relatively simple, as it involves only one DoF motion. Designers should consider how to arrange the components in a rational way, compatible with the large span ratio of the wing. The folding speed of the wing needs to be as fast as possible, and the reliable drive options are mainly servo motor drive and hydraulic cylinder drive, etc.

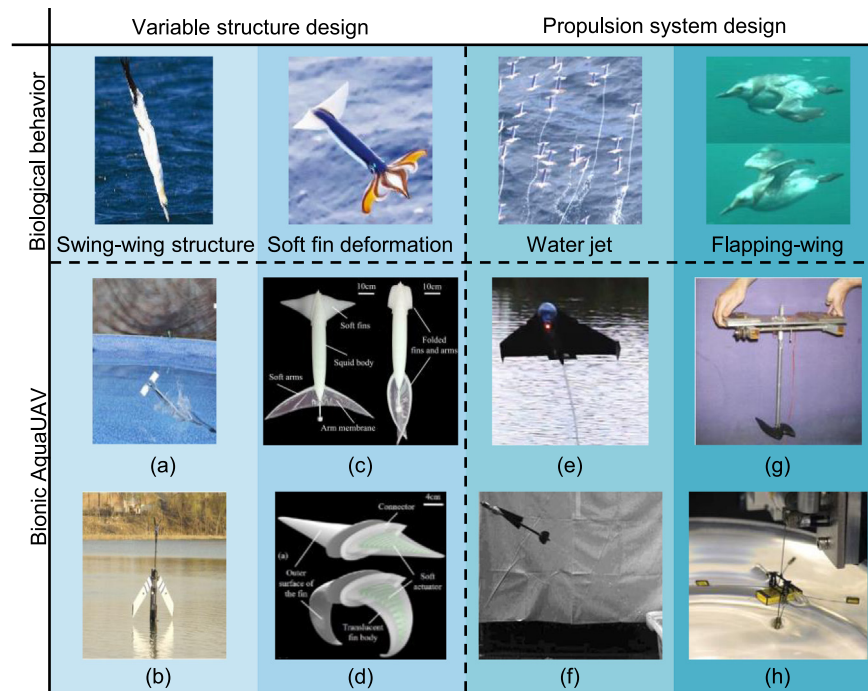


Fig. 6. Typical AquaUAV prototype from: (a) Plunge-diving prototype from MIT Lincoln Lab [112], Copyright©2012, MIT. (b) Gannet Prototype from Beihang University [105], Copyright©2013, IOP Publishing. (c) Flying squid prototype from Beihang University [78], Copyright©2019, IEEE. (d) Soft squid-inspired wing from Beihang University [113], Copyright©2019, IEEE. (e) Explosive jet prototype from Imperial College London [114], Copyright©2019, AAAS. (f) Water-jet with propeller propulsion from Imperial College London [115], Copyright©2017, The Royal Society. (g) Multimodal wing from University of Bristol [116], Copyright©2010, IOP Publishing. (h) Explosive jet insect prototype from Harvard University [117], Copyright©2017, AAAS. Besides, swing-wing structure (Copyright©, David Tipling), soft fin deformation and water jet (Copyright©2013, IOP Publishing (Kouta Muramatsu)), flapping-wing ([116], Copyright©2010, IOP Publishing).

4.2.2. Soft fin deformation

The flying squid holds paired fins tightly around the body and folds carpal fins in the body-axis direction during the water-air transition. Hou et al. used silicone to cast bionic paired and carpal fins [78]. The fins had built-in pneumatic bellows, and the folding and unfolding motion were controlled by high-pressure gas. During the takeoff process, the high-pressure gas was released to fill the air cavity, the paired fins wrapped around the body and the carpal fins folded backward (see Fig. 6(c) and Fig. 6(d)) [113].

The difference in lift caused by different spread ratios of two sets of fins may assist the AquaUAV to complete some flight maneuvers, e.g., turns, emergency stops and climbing. However, the swing-wing structure only achieve unidirectional folding and unfolding and need rudders setting to help with flight control. However, the deformed soft fin structure increases the weight of the whole prototype, which puts higher demands on the power system. That is because drive of soft fins requires another independent drive systems, such as pneumatic drive, shape memory alloy driving, etc.

4.3. Propulsion system design

The aquatic-aerial propulsion mechanisms commonly employed by aquatic-aerial amphibians are morphing wings, tapping flippers, water jet propulsion, and flapping fins. So far, water jet propulsion and wing flapping has been applied successfully in AquaUAV.

4.3.1. Water jet

The water jet propulsion system can generate a huge momentum to propel the prototype to take off. Zufferey et al. used calcium carbide powder as solid power [114]. Calcium carbide powder reacted with water to produce acetylene. The acetylene converging in the water tank was ignited by the spark plug to

form a huge explosive impact, and these impacts squeezed the water backwards to form the jet (see Fig. 6(e)). In addition, the propeller can be applied to cooperate with water jet. Siddall et al. used compressed carbon dioxide gas as the power source of the water jet (see Fig. 6(f)) [115]. When the prototype flies into the air, the propeller was opened to provide flight power. A similar propulsion idea was also used by Guo et al. [121], for which preliminary design and wind tunnel tests were conducted.

Prototypes using water-jet propulsion usually broke out of the water before the water ran out. While in the air, the water tanks cannot recharge, and the water jet propulsion system cannot provide sustained propulsion. We prefer to add the propeller to provide additional thrust in conjunction with gliding flight to increase the flight distance. Carrying two propulsion systems will increase the mass and size of the prototype. Therefore, the prototype need focus on a trade-off design of the prototype loads and locomotion performance.

4.3.2. Flapping-wing

Gannet and common guillemot use morphing wings as a means of amphibious propulsion. Lock et al. developed a 2 DoF multimodal wing prototype (see Fig. 6(g)) [116,122–124]. From theoretical design, physical construction to water tunnel testing, they tested the performance of this multimodal wing underwater and in the air, separately. Chen et al. developed an insect-scale wing flapping robot [117]. The robot weighed only 175 milligrams (see Fig. 6(h)), which had multimodal wings to flap underwater and in the air. When transmit from underwater, it used explosive gas generated by electrolysis of water to increase its buoyancy, thus performing passive uplifting. Upon reaching the surface, it ignited the hydrogen-oxygen mixture gas and achieved an explosive water jet takeoff.

Considering the locomotion performance of the prototype, like propulsion force and swimming speed, the researchers tend not

to apply morphing wings for AquaUAV. However, we believe that flapping-wing is perhaps the most promising form of propulsion for AquaUAV in whole locomotion process. Through the differential force of flapping, AquaUAV can achieve full process water-air locomotion using one set of propulsion system, like water entry, swimming, water exit and air flight. And some maneuvering motion may also be achieved, although the flapping effect may be limited.

5. Conclusions

In this article, we seek bioinspiration from the aerial-aquatic amphibians for the development of AquaUAV. We started with the evolutionary trade-offs of multi-mode locomotion in aerial-aquatic amphibians. The investigation included aerial organisms represented by gannet and cormorant, and aquatic organisms represented by flying fish and flying squid. We reviewed the multi-mode locomotion processes of these organisms. By summarizing their amphibious evolutionary trade-offs, aerial UAV and underwater UAV may gain inspiration to develop variable structural layouts to adapt to underwater swimming and aerial gliding, separately. Aerial organisms commonly use morphing wings and flippers tapping for underwater diving, and aquatic organisms commonly use water jet and flapping fin for flight locomotion. These propulsion methods allow aerial-aquatic amphibians to have the ability to move both in water and in the air. The propulsion system of the AquaUAV can find some breakthrough here to obtain greater propulsion force and efficiency. Besides, the structural characteristics and morphological parameters of the aerial-aquatic amphibian may guide the shape, size design and structural layout optimization of the AquaUAV, which help the prototype to reduce the resistance and enhance the locomotion performance between water and air.

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.

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