Unmanned Systems, Vol. 9, No. 3 (2021) 263–282
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DOI: 10.1142/S2301385021410028

Unmanned Systems
https://www.worldscientific.com/worldscinet/us

Survey on the Development of Aerial–Aquatic Hybrid Vehicles

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As the development of mobile robots matures, there is an increasing amount of interest in expanding the functionality of such robots through developing multimodal locomotion. As compared to land–water or land–air hybrids, the design of air–water vehicles is much less straightforward due to the fact that both mediums are three-dimensional fluid spaces and there is inherent disparity in fluid properties between them. As such, the development of these vehicles has received limited attention until very recently. Nevertheless, the potential applications of such vehicles range widely from military surveillance, oceanic data collection to heterogeneous robot team operation, which has led to an increasing number of projects working on aerial–aquatic hybrid mobility. In this paper, we discuss the fundamental challenges associated with aerial–aquatic hybrid locomotion as well as the necessary trade-offs in design decisions. We also summarize and review the existing work and prototypes of aerial–aquatic vehicles that have been designed thus far, analyzing the range of solutions that have been adopted to solve the aforementioned challenges. Lastly, the limitations of these solutions are analyzed to offer a perspective on how future developments in the area can enable greater functionality for the concept.

Keywords: Mobile robots; multimodal locomotion; hybrid robots.

1. Introduction

The idea of a multimodal vehicle that can travel in both water and air first emerged in works of fiction dating back to Jules Verne's novel *Master of the World* in 1904. Just as how earlier works of science fiction inspired the development of the modern submarine, the idea of a *flying submarine* had reportedly been pursued by the Danish [1] and Russian [2] military in the 1930s in the form of submersible seaplanes. While some documentation exists about these trials, little evidence shows that these attempts went beyond the design phase or demonstrated any degree of functionality, and these plans were eventually abandoned by the 1950s. The concept then remained undeveloped for decades until the development of unmanned aerial vehicles (UAVs) matured in the mid-2000s. In 2006, the US Navy put into development the Cormorant [3, 4], a submarine-launched UAV that features retractable gull wings. Although initial tests were performed, the project was ceased before the proposed design was fully realized.

Interest in the topic resurfaced in the 2010s when research laboratories began to expand into the area of multimodal robots. While basic amphibious land–water and land–air robots can be designed by integrating two separate propulsion systems into a single vehicle, achieving aerial–aquatic multimodal locomotion is much less straightforward due to the complex and differing nature of the two fluid mediums. Since both air and water are three-dimensional fluid spaces, simply holding position requires the robot to negate the forces of gravity and buoyancy, unlike terrestrial navigation where the ground plane is defined by the terrain that the robot is moving on. While the gravitational weight of the robot remains the same in air and water, the disparity in fluid density results in a significant buoyancy force when submerged. This additional phenomenon has implications on both vehicle stability and locomotive

Received 4 July 2020; Revised 16 November 2020; Accepted 16 November 2020; Published 10 December 2020. This paper was recommended for publication in its revised form by editorial board member, H. T. Liu.
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efficiency as it alters the dynamics of the vehicle. In addition, the medium of water also poses challenges separately to aspects such as propulsion, communication and waterproofing, further complicating the design considerations. Hence, working aerial–aquatic prototypes still remain significantly less prevalent than other types of multimodal robots. Despite a range of solutions that have been proposed and demonstrated to various degrees of success and functionality, there is as yet no common consensus on an optimal solution for such a robot and development remains at an exploratory stage with only a small number of fully functioning prototypes.

In this paper, we will build on the work of earlier reviews in this area, namely the earliest survey on aerial–aquatic vehicles by Yang *et al.* [5] and a subsequent one by Qiu and Cui [6], by summarizing the recent development of prototype vehicles and providing an update to the latest trends and progress of this unique class of multimodal vehicles. We first discuss the motivation for these vehicles, and the potential applications where the unique capabilities of such designs are specifically needed, in Sec. 2. As the defining parameters of the design problem, the challenges specific to aerial–aquatic robots are then outlined in Sec. 3. By looking at the various medium properties, the contradicting requirements provide an explanation on the difficulty of aerial–aquatic designs and the limited development that they have received thus far. The development of existing aerial–aquatic prototypes is then summarized in Sec. 4, where the various solutions adopted are classified based on the vehicle type and the steps taken to deal with the aforementioned challenges are reviewed. Section 5 then breaks down the typical mission profile of an aerial–aquatic vehicle into four key stages, and the solutions that have been proposed to deal with the unique problems of each stage are analyzed. As the development of these vehicles gradually progresses from partial-feature examples to full-feature ones, we pay specific attention to the approaches adopted by existing full-feature prototypes to understand the requirements of integrating these methods into a single working vehicle. Lastly, the lessons learnt from the recent developments of aerial–aquatic vehicles are summarized in Sec. 6 and the future directions for such vehicles are proposed.

2. Motivation

The real-world outdoor environment is often harsh and complex. Just like the concept of amphibious vehicles and land–air hybrids, aerial–aquatic vehicles expand the range of operation and application possibilities of mobile robots by being able to operate in two mediums. While aerial vehicles are often used to access remote areas due to their range and ability to overcome terrestrial obstacles, such areas often do not offer suitable areas to land. In these cases, the presence of water is frequently an obstacle in itself. There also exist many applications where aerial vehicles may come into contact with water or would be required to withstand such contact without damage. In these cases, having a vehicle that can not only survive, but also operate in both air and water would be incredibly useful.

The uniqueness of aerial–aquatic vehicles, as compared to other multimodal ones is the fact that they can also benefit from the properties of the surrounding fluid. The high density of water implies that there will be a significant buoyancy force acting on any submerged vehicle. This can be taken advantage of to reduce the energy needed for the vehicle to hold its vertical position by calibrating the buoyancy force to offset weight. This will allow the vehicle to remain in an idle state at a given position in a much more energy efficient manner as compared to aerial flight, where the vehicle has to generate sufficient lift in order to counter its weight. In addition, operating in water also provides a natural cover when stealth is required due to the reduced visibility caused by the phenomenon of light refraction and dispersion. On the other hand, the low density of air results in significantly lower drag forces, making high speed travel possible and more efficient than in water. Together, a vehicle that can utilize the features of these two mediums can use the properties to offset the limitations of the other medium.

Though the development of aerial–aquatic vehicles has yet to mature, the emerging interest in the area indicates the potential for these robots. There are many applications, ranging from industrial to military, that would require the specific ability to traverse both air and water. These include the following:

- Structural inspections on ship hulls, maritime infrastructure, oil platforms, bridges and pier structures.
- Survey of water bodies such as lakes, lagoons and rivers, which can be done quickly through aerial deployment instead of relying on manual data collection or deploying underwater vehicles manually from man-operated surface vehicles.
- Access to remote areas where land-based vehicles cannot reach or where air and water are the two primary mediums, i.e. large water bodies such as the open ocean.
- Extreme weather conditions where single mode vehicles cannot operate.
- Military applications such as launch and recovery from a submarine or aerial platform, heterogeneous teams or cross-medium missions.

While the development of aerial–aquatic prototypes is still in its early stages, the groundwork has already been laid for the future use and inclusion of such vehicles in the bigger picture of mobile robots. For example, the use of aerial vehicles for remote water sampling [7] can be further improved by using a hybrid vehicle which can collect samples at different depths. The use of robots in the response to disaster areas has already been implemented in the relief efforts of Hurricane Wilma [8], the Great Eastern Japan Tsunami [9] and the Fukushima nuclear disaster [10], and the use of a multimodal vehicle has been proposed to be potentially useful in overcoming the obstacles that limit existing mobile robots in these situations. The use of multimodal hybrid vehicles as part of a larger team of mobile robots has also been proposed, with the path planning of such coordinated missions being presented in [11, 12]. The wide range of potential applications that these vehicles can be adopted for has created the impetus for such designs, which will likely receive considerable attention and development especially as the design of novel mobile robots continues to mature.

3. Challenges of Aerial–Aquatic Operation

The number of challenges faced by multimodal vehicles are significantly greater than that of a standard mobile robot. In addition to dealing with the conditions of each individual environment separately, they also have to resolve any contradicting requirements that may arise and manage the transition between mediums. As the fundamental nature of different mediums varies, the locomotive requirements of each environment may not necessarily align with the other, resulting in design trade-offs that have to be balanced. This is exactly the case for aerial–aquatic hybrid robots and the very reason that the development of such vehicles still remains in its early stages today.

3.1. *Contrasting medium properties and design goals*

The locomotion method of any mobile robot and hence everything ranging from its physical design to propulsive method depends on the properties of the medium that it operates in. For fluid mediums such as air and water, the medium properties of density and viscosity directly affect the dynamics of any moving vehicle as it is associated with both the generation of thrusting force and body drag, and this has resulted in common design trends which most functional vehicles follow. The values of density and viscosity of air and water differ greatly as shown in Table 1. As these property values of water are several magnitudes higher than air, any moving body in the medium would experience significantly larger fluid forces and naturally move at a slower timescale. This can be observed through the differences between typical aerial propellers, which are long and slender and operate at high rotational speeds, and aquatic propellers, which are typically smaller in diameter with broader blade areas and spin at much slower speeds.

Table 1. Fluid properties of air and water at 20°C.

		Air	Water
Density (kg/m^3)	ρ	1.204	998.0
Dynamic viscosity (kg/(ms))	μ	1.825×10^{-5}	1.002×10^{-3}
Kinematic viscosity (m^2/s)	ν	1.516×10^{-5}	1.004×10^{-6}

While the vertical coordinates of terrestrial robots are determined by the ground plane, aerial and aquatic robots are mostly not constrained in this way as they operate in three-dimensional fluid space. As such, being in an idle state in a particular position in space is no longer straightforward due to the external forces that are acting on the vehicle. The first force that will act on any vehicle body is its weight, caused by gravitational acceleration of the vehicle's mass. In addition to weight, the displacement of fluid volume will result in a buoyancy force that is proportional to the density and volume of the fluid displaced. As the density of water is more than 800 times that of air, the buoyancy force of any submerged vehicle will be significant.

For aerial flight, one of the fundamental design goals is to minimize the weight of the vehicle as this would reduce the amount of lift that needs to be generated. Any additional weight would require more lift, which is typically generated either directly through thrusters acting in the lifting direction or by lifting surfaces. Increasing the lift generation in any way will inherently add to the drag of the vehicle, further compounding the need for more thrust and power to overcome the added drag. Therefore, weight is a key design parameter that should always be minimized in aerial vehicle design.

On the other hand, the presence of buoyancy often counters some if not all of a vehicle's weight when submerged underwater. If the density of the vehicle is less than the density of the water medium, then there would be a net upthrust acting on the vehicle. In this case, the vehicle would have to exert a downwards thrusting force to hold vertical position, which is the opposite of aerial locomotion. In aquatic vehicle design, there is also the possibility of calibrating the vehicle's overall density to be near that of the surrounding fluid so that minimal force is needed to hold vertical position, which is commonly known as obtaining neutral or near-neutral buoyancy. As such, the key design parameter in water is the vehicle's overall density, which is also related to its volume in addition to its weight.

For a vehicle that has to incorporate operation in both air and water, the goal of minimising weight in air has to be balanced with obtaining near-neutral buoyancy in water.

This is likely to be contradictory in many established designs as lightweight structures used to reduce weight often implies low density, which will produce a highly positively buoyant vehicle that is unsuited for underwater operation. While the buoyancy can be reduced by compactly packaging the vehicle to increase its density by reducing volume instead of increasing weight, many designs such as large wing areas do not lend themselves well to this solution.

3.2. *Static stability*

While the absolute values of a vehicle's weight and volume will determine its net buoyancy when submerged, the volume and weight distribution within the vehicle will affect the position of the center of gravity (COG) and center of buoyancy (COB). This has implications on the static stability of the vehicle if the two points do not coincide. For a submerged body that is neutrally buoyant, static stability can only be achieved if the COB and COG act vertically through the same point and the COB is above the COG. Otherwise, the default orientation or attitude of the body will rotate until static equilibrium is achieved. As such, the volume distribution, which is typically not a design factor in aerial platforms, becomes a significant parameter for aerial–aquatic vehicles. While buoyancy devices can be used to adjust the values of weight and buoyancy and position of COB and COG, such mechanisms will further add to the weight requirements, which is a key design trade-off for the aerial function of the vehicle as mentioned previously.

3.3. *Additional challenges of being submerged*

Besides the implications of the fluid densities and viscosities on a vehicle's design, the distinctive nature of water also demands specific requirements that are unique to the medium. Firstly, the conductivity of water means that electronic components of the vehicle cannot be exposed. To prevent water damage, submersible vehicles typically feature a sealed hull or main body where these components are located. Although there are established waterproofing methods and hull designs for submersible vehicles, these are often large and heavy to withstand the hydrostatic pressure of being submerged. For small-scale vehicles which do not require a pressurized cabin, the walls of the enclosed hull have to be sufficiently thick to match the required depth rating. Any openings will also have to be sealed using solutions such as gaskets or o-rings and held together with clamps, bolts or spring-loaded latches. While this additional weight from the waterproof casing is not an issue for exclusively submersible vehicles due to the presence of buoyancy underwater, it becomes an additional payload that will compromise performance in the aerial phase of an aerial–aquatic vehicle.

Furthermore, many established communication and localization methods, such as radio communication, do not penetrate well in water due to high attenuation rates. This means that standard radio communication for data transfer and control will be limited, and localization using Global Positioning System (GPS) is not possible. Although there are established underwater alternatives used in submarines and submersible vehicles such as acoustic-based systems, these are typically large and bulky, making them unsuitable for vehicles that also have to execute aerial flight.

4. Prototype Developments

In an earlier survey of aerial–aquatic vehicles done by Yang *et al.* [5] in 2015, the authors classified the existing prototypes into three broad categories: seaplane-type, submersible-launched UAVs, and fully functional aquatic UAVs. The first group, seaplanes, are aerial vehicles that only come into contact with the water surface and do not venture deeper. Submersible-launched UAVs, on the other hand, are capable of prolonged periods of being submerged, but are otherwise passive and require external systems to transit to their primary aerial phase. Lastly, the authors identified the initial attempts at making a fully functional aerial–aquatic vehicle which can be actively self-propelled and controlled in both mediums. Despite some initial experimental prototypes which demonstrated potential solutions to the various challenges, there were no full-featured aerial–aquatic prototypes produced at that time. Although another review was done by Qiu and Cui [6] in 2019, this survey was mostly a reiteration of the work presented in [5] and did not provide new insights into the existing and prospective solutions to the problem. The development of aerial–aquatic vehicles has progressed significantly since, and here, we will discuss the recent developments in the area. While the earlier works were mostly focused on partial-function aerial–aquatic vehicles, such as the first two categories described above by Yang *et al.* [5], here, we will focus on full-function aerial–aquatic vehicles, that is, vehicles that are fully mobile and can be actively controlled in both air and water.

Existing aerial–aquatic vehicles, both partial and full-feature, can be classified according to the hardware platforms that they adopt. A large majority are based on the established aerial vehicle design of fixed wing planes and multirotors. These two types of platforms vary primarily in their aerial operation, with characteristics similar to the precursor aerial counterparts that they are based on in terms of flight time and manoeuvrability. Nevertheless, the differences in hardware structure also affect the transition and operation underwater. There has also been hybrid platform prototypes which integrate more than one of these platforms into a single vehicle in attempts to better adapt the vehicle to each medium. Another class of vehicles includes those which feature bio-inspired designs such as flapping wings. These existing prototypes are categorically summarized in what follows.

4.1. *Fixed wing-based vehicles*

Many of the early designs of aerial–aquatic vehicles were based on the conventional fixed wing plane. As a well-established aerial platform, the fixed wing layout characteristically features a relatively slender fuselage with a main wing which is a lifting surface that extends out symmetrically and perpendicularly from the centerline of the fuselage. A secondary smaller lifting surface near the tail commonly acts as a stabilizer. Lift is generated through airflow across the lifting surfaces when there is forward airspeed, and attitude control is achieved through the deflection of control surfaces such as the ailerons, elevators and rudder on the main wing and tail.

The earliest application of aerial vehicles that comes into contact with water is in the form of seaplane-type vehicles, which are fixed wing aircraft with the ability to land on the water surface. While such vehicles are water resistant, they are not built to withstand being fully submerged or function below the water surface. Adding on to the examples of these seaplane-type UAVs in [5], which are mostly for military and reconnaissance use, recent research projects have offered more unconventional ideas and possibilities for this class of vehicles. In 2017, the *SUWAVE* [13] (Fig. 1) from Sherbrooke University was designed as a prototype lake-hopping aerial vehicle that uses water bodies as a landing space to recharge via solar panels. The prototype is a flying wing that can land on water bodies and subsequently retake

Fig. 1. The SUWAVE is a flying wing vehicle that uses water surfaces as resting areas to perform 'lake-hopping'. Image reproduced with permission from [13], courtesy of the authors and publishers.

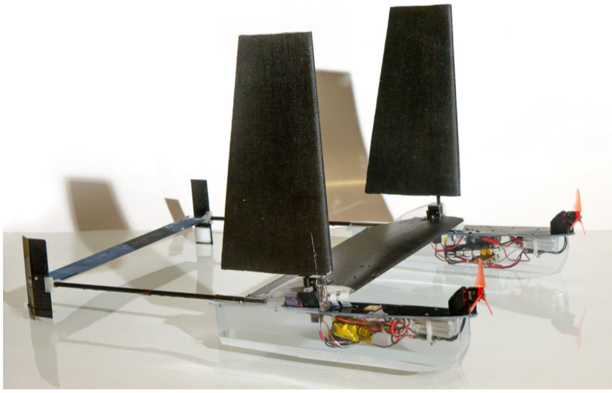


Fig. 2. The SailMAV is a fixed wing vehicle that can be converted into a sail boat configuration. Image reproduced with permission from [14], courtesy of the authors and publishers.

flight through a hinged body that allows the propeller to point vertically upwards. This allows the vehicle to take-off vertically before the wing rotates and snaps into place passively to return to standard fixed wing operation. In 2019, Zufferey *et al.* from Imperial College London presented the *SailMAV* [14] (Fig. 2), which is a twin-hulled fixed wing plane that can land and take-off on water surfaces. Unlike earlier seaplane-type designs, the *SailMAV* is able to fold its wings vertically and control their incidence angles so that they can act as sails, allowing energy efficient surface movement.

Besides the straightforward application of seaplane-type vehicles, the fixed wing configuration also lends itself to the application of submarine or submersible launched vehicles as the wings can be simply swept backwards and folded to create a slender streamlined body which is suitable for launch through tubular cannons and missile launchers. The earliest suggestions of the modern aerial–aquatic vehicle concept, which is a vehicle that can both withstand being submerged and perform aerial flight, is the DARPA-associated project *Cormorant* [3, 4] by Lockheed Martin in 2006. As a submarine-launched and recovered vehicle, the design of the *Cormorant* features retractable gull wings that allow the vehicle to fit within the launch tube of the mothership. As a military-associated project, limited details are available; and although initial tests were performed, the project was ceased by 2008. In 2013, the Naval Research Laboratory developed the *XFC UAS* [15] (Fig. 3), which is a foldable X-wing vehicle that is powered by an electric fuel cell. With an endurance of more than six hours, the *XFC UAS* can be launched from a missile launch canister. In 2017, Lockheed Martin's *Outrider* [16, 17] was developed, which is another military-use canister-launch UAV that features retractable wings.

The development of other partial-feature experimental concepts featuring fixed wing configurations from 2009 to

Fig. 3. The XFC UAS from the Naval Research Laboratory. Image reproduced with permission from [15], courtesy of the authors and publishers.

Fig. 4. The AquaMAV executing a plunge dive into the water. Image reproduced with permission from [24], courtesy of the authors and publishers.

2014 is well summarized in [5]. During this period, the concept of an aerial–aquatic vehicle was commonly framed as a fixed wing plane that is able to execute a plunge diving manoeuvre to enter the water. In 2012, *Project Gannet* [18] from the MIT Lincoln Laboratory presented a prototype fixed wing vehicle that can fly, fold its wings and plunge dive into the water. Though it is waterproofed, this initial prototype was unable to re-emerge from the water body or retake flight. In 2013, a team from Beihang University studied the impact dynamics of a plunge diving *Bionic Gannet* prototype with swept-back wings through both empirical experiments [19] and computational fluid dynamics (CFD) simulations [20, 21]. The authors also proposed a concept aerial–aquatic vehicle in [22] which can perform plunge diving and subsequently retake flight by vertically exiting the water after using a balloon system to right the vehicle. A similar concept of a folding wing vehicle capable of water entry via plunge diving is the *AquaMAV* [23–25] (Fig. 4) from Imperial College London. Besides the flight and plunge diving capabilities, the *AquaMAV* also featured a water jet thruster powered by compressed air [26] that launches the vehicle out of the water to regain flight. This water jet launcher mechanism was further refined in [27]. This water exit method, inspired by the flying squid, provides a continuous thrusting force during the transition out of water and allows the vehicle to quickly launch itself clear of the water and into air. As this system requires preloaded compressed air, it is only able to perform the water exit launch once during its mission.

While these partial-feature prototypes and experimental concepts provide useful insights on potential solutions to the design of aerial–aquatic vehicles, the goal of a multimodal cross-medium vehicle is still to achieve full function and mobile operation in both mediums. In recent years, the fixed wing platform has also been used as the basis for aerial–aquatic vehicles that are meant for more extensive underwater operation in addition to aerial flight. Many of these vehicles operate underwater under the same principles as in air, using its thruster, often a single propeller, to produce forwards movement while the same control surfaces are used to control the roll, pitch and yaw of the vehicle.

In 2014, the *Flying Fish* [28] from Beihang University demonstrated a different concept of a vehicle that is a combination of a seaplane and submarine. To transition from aerial to underwater operation, the *Flying Fish* first performs a runway landing on the water surface before diving by ingesting water into internal water tanks. Despite not engaging in any plunge diving manoeuvres, the vehicle also features swept-back wings upon transition to aquatic mode to reduce drag underwater. Water inlets that flood the internal cabins allow the vehicle to reduce its buoyancy to performing diving, and underwater locomotion is powered by an underwater propeller. Water-to-air transition is a reverse of this process, and the vehicle performs a typical seaplane take-off to retake flight. Weighing 12 kg and measuring almost 2 m in length, the *Flying Fish* is significantly larger than many of the experimental aerial-aquatic prototypes, and requires a large take-off and landing distance of more than 30 m and 40 m, respectively. In addition, the transition time required to submerge the vehicle and re-emerge from the water is around 15–20 min each, which is relatively time consuming when considering such a vehicle's mission profile.

In 2017, the North Carolina State University together with Teledyne developed two similar aerial–aquatic prototypes (Figs. 5 and 6) that were presented in [29, 30], respectively.

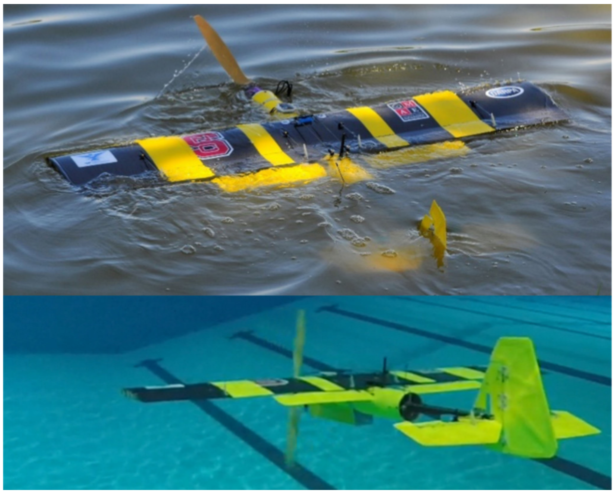


Fig. 5. The Eagleray XAV by North Carolina State University and Teledyne. Image reproduced with permission from [29], courtesy of the authors and publishers.

Fig. 6. The seabird-inspired fixed wing hybrid UAV–UUV by North Carolina State University and Teledyne. Image reproduced with permission from [30], courtesy of the authors and publishers.

Both works are based on the same fundamental vehicle configuration and mission profile, with the prototype in [30] having an additional aquatic propeller near the tail of the vehicle while [29] uses the same thruster for both aerial and aquatic movement. To adapt for underwater locomotion, the fixed wing plane structure features floodable wing compartments to reduce the overall buoyancy of the vehicle when submerged. Besides conventional aerial flight and transitioning via soft runway landing on water surfaces, the authors also proposed and demonstrated an unassisted vertical water exit. To transition from water to air, the vehicles settle in a vertical nose-up position just beneath the water surface before accelerating using its aerial propeller to gain vertical speed while draining the flooded wing components simultaneously [31].

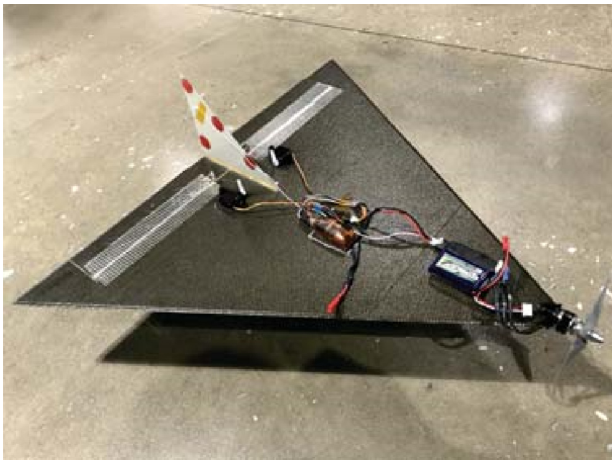
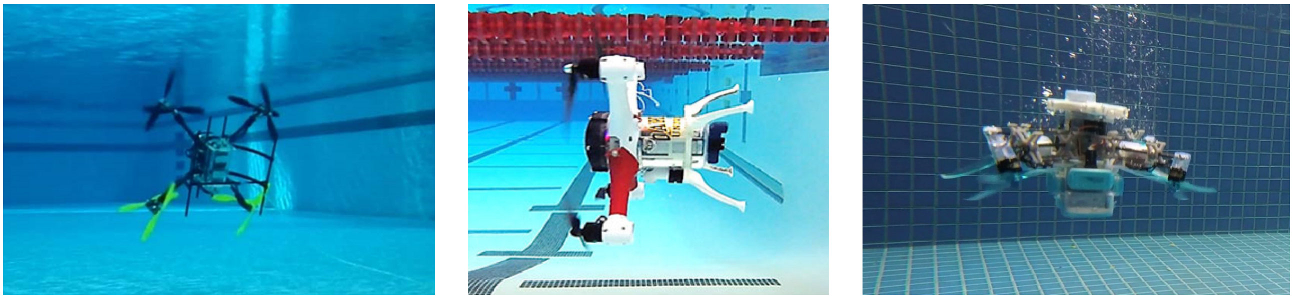


Fig. 7. The Flying Fish delta wing prototype from John Hopkins University's Applied Physics Lab. Image reproduced with permission from [32], courtesy of the authors and publishers.

In 2018, Moore *et al.* [32] from John Hopkins University's Applied Physics Laboratory developed a fixed wing aerial–aquatic prototype that features a delta wing configuration (Fig. 7). Unlike earlier designs that feature morphing mechanisms or adaptive structures, the entire vehicle and carbon fiber wing is physically identical when operating in both air and water. The authors also demonstrate the water exit method proposed which is to build up speed underwater before breaking the surface directly at an inclined body angle. Closed-loop control of this transition was later discussed in [33].

4.2. *Multirotor-based vehicles*

Besides conventional fixed wing planes, the use of multirotors as an aerial platform has become increasingly widespread in the last 15 years as the technologies in control systems mature. With typically four, six, or eight coplanar rotors, multirotors differ from fixed wing planes as they do not have lifting surfaces and generate lift entirely through thrust that is directed vertically. Unlike the control surfaces used in fixed wing configurations, the attitude and movement of multirotors are controlled through varying the relative rotor speeds to generate rotational accelerations in roll, pitch and yaw. This allows them to hover and execute finer movements than fixed wings, which enables navigation of tighter spaces and cluttered environments, but they do so at the cost of higher power consumption due to the large number of spinning motors at work. Nevertheless, the inherent structural design of multirotors, with all thrusters directly generating vertical lift, allows for a large payload capacity, which is observed in the preference for multirotors in applications such as the last-mile delivery of goods and parcels.



(a) (b) (c)

Fig. 8. Multirotor-based aerial–aquatic prototypes: (a) Naviator; (b) LoonCopter; (c) Morphable Hybrid Quadrotor. Images reproduced with permission from [39, 43, 45], courtesy of the authors and publishers.

The conventional quadrotor platform can be adapted to create a partial-feature aerial–aquatic vehicle by simply making the vehicle waterproof. Waterproof quadrotors are useful in applications such as coastal survey or lifeguard operations as there is a high possibility of coming into contact with water. Such vehicles are available commercially ranging from hobby-grade quadrotors to larger ones for environmental monitoring [34] and professional filming uses [35, 36]. While these partial-feature multirotors are not designed for aquatic operation, the ability to withstand water contact allows them to land on water bodies and remain idle in such a position. Tasks such as underwater filming [37] are also possible with a downwards facing camera on the vehicle. Regaining flight, though, is usually subjected to the environmental conditions and may only be possible in situations where the water is calm with minimal disturbances.

Similarly, a waterproof multirotor can also be designed to launch from beneath the water surface. Due to the typical hardware configurations and coplanar thruster layout, underwater launched multirotors have not been designed to be ballistically shot at high speed through launch cannons like fixed wing-based vehicles. An example of such underwater launched multirotors is the prototype *CRACUNS* [38] (Fig. 9) from the John Hopkins University's Applied Physics Laboratory, which is a waterproof quadrotor that can remain submerged in a hidden dormant state until it is deployed, rising to the surface and performing its task. Although the *CRACUNS* does not display active aquatic function, it is able to remain submerged for extended periods of time while remaining functional when it emerges from the water through its waterproof shell design and anti-corrosive coatings on its motors.

Fig. 9. The CRACUNS [38] from John Hopkins University's Applied Physics Lab. Image credits: Johns Hopkins Univ. Applied Physics Laboratory.

The first example of a full-featured aerial–aquatic hybrid vehicle is the multirotor-based *Naviator* (Fig. 8(a)) presented by Maia *et al.* [39, 40] in 2015. Unlike the other waterproof quadrotors described above, the *Naviator* can be actively controlled in both mediums and transit between the two without external devices or intervention. This work features several breakthroughs for such multimodal vehicles. Firstly, the authors identify that the orientation of the vehicle's thrusters will have to be primarily horizontal when underwater as opposed to vertical in air. This is due to the presence of buoyancy when submerged, which will offset some if not all of the vehicle's weight, resulting in a much smaller net force acting on the vehicle. In addition, the higher density and viscosity of the medium imply significantly higher drag, hence the aerial multirotor solution of effectively moving in surge and sway by directing small components of the vertical thrust in those directions through applying rotations in pitch and roll, respectively, would be ineffective. Secondly, the feasibility of using the same set of aerial propulsion system was briefly discussed and demonstrated empirically, although not thoroughly investigated. Lastly, the use of an X8-octocopter layout allows the vehicle to have its thrusters arranged in two layers, ensuring that the transition between mediums can be performed as at least one layer of thrusters would be completely in one medium and clear of the intermediate transition stage at any time. The trajectory tracking and control of the *Naviator* was then subsequently presented by Mercado *et al.* in [41, 42].

In 2016, a team from Oakland University developed the *LoonCopter* [43] (Fig. 8(b)), which is a quadrotor capable of surface and submerged movement through the use of an active buoyancy control system. This feature introduces a more formal transition from aerial operation to aquatic operation as it is activated after the air-to-water transition and then in reverse before the water-to-air transition. Unlike the *Naviator*, which requires active thruster inputs to produce the rotational accelerations to tilt the vehicle body in the direction of motion, the buoyancy control system of the *Looncopter* not only adjusts the buoyancy but also the default attitude of the vehicle when submerged. Through positioning the ballast tank of the buoyancy control system strategically, the vehicle will tilt forwards when the tank is filled, redirecting the thrusters in the horizontal plane. This allows forward movement to be more efficient as the vehicle does not need to actively engage in a rotational movement to direct thrust in the direction of motion.

In 2019, Tan and Chen [44] presented a quadrotor-based morphable aerial–aquatic vehicle (Fig. 8(c)) that features rotation of the thrusters to redirect the thrust in the direction of motion when submerged. This proposed approach overcomes the restrictions of using the fixed hardware configuration of a standard quadrotor underwater, which include the limited control authority in surge, heave and sway, commonly the main thrust directions required when underwater. While earlier aerial–aquatic quadrotors with a standard hardware layout needed to rotate the entire vehicle body, this solution instead rotates only the thrusters about their respective arm axes. The morphing mechanism is designed to be coupled and symmetric, allowing the rotation of the thrusters to be controlled by a single actuator. A direct mechanical linkage consisting of four interlocking miter gears at the core of the vehicle's frame structure forms the tilting mechanism. A second generation prototype of the vehicle was subsequently presented in [45] and further updated in [46].

4.3. *Hybrid platform vehicles*

As the demands of a multimodal vehicle are essentially a combination of two different operating modes, it is perhaps intuitive to use a combination of more than one platform or locomotion method to overcome the design challenges. Although most of the early prototypes are based primarily on one type of established aerial platform, there are recent examples which integrate a combination of these platforms into a single hybrid vehicle.

A major difference that sets apart these hybrid designs from the fixed wing and multirotor-based platforms above is the use of different propulsion systems or methods in the two mediums. Although the drastically different medium properties result in very different torque and speed requirements on typical thrusters, the prevalent method for propulsion systems is to use the same aerial propulsion system underwater. This is often the preferred solution to minimize excess weight that will affect aerial flight. While this has been demonstrated to be a possible solution, it implies that the vehicle's locomotive efficiency is severely compromised in the aquatic phase. The alternative of using two separate propulsion systems will naturally improve the propulsive performance in both mediums and result in more balanced aerial and aquatic function.

Fig. 10. A prototype of the HUAUV from Universidade Federal do Rio Grande. Image reproduced with permission from [49], courtesy of the authors and publishers.

The simplest example of such hybrid platforms are multirotors with additional sets of aquatic thrusters, essentially combining the design of an aerial multirotor with an underwater remotely operated vehicle (ROV). Unlike the multirotor-based vehicles above, these vehicles do not activate the aerial propellers when submerged. In 2014, Drews *et al.* presented such a concept called the *Hybrid Unmanned Aerial Underwater Vehicle (HUAUV)* [47] (Fig. 10). The proposed design features four separate aquatic propellers beneath the four aerial propellers of the quadrotor. The authors subsequently performed theoretical analysis and simulation of the attitude control for such a vehicle in [48], and performed tests to investigate the impact of thruster configurations in [49].

In 2018, Lu *et al.* [50] proposed a hybrid aerial–aquatic vehicle which is a combination of an aerial quadrotor, fixed wing, and underwater glider. The working prototype *NEZHA* [51] (Fig. 11) was subsequently presented in 2019. While the primary structure of the *NEZHA* is similar to a standard quadrotor, its operation differs significantly from the multirotor-based vehicles in the previous section as it is capable of forward flight in air and acts as an underwater glider when submerged. By using a buoyancy controlled locomotion method underwater as opposed to thrusters, the

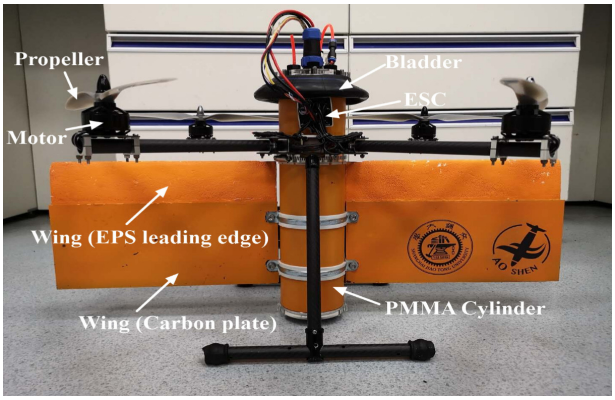


Fig. 11. The NEZHA prototype from Shanghai Jiaotong University. Image reproduced with permission from [51], courtesy of the authors and publishers.

prototype is capable of extended endurance as it is significantly more energy efficient.

In 2019, Vyas *et al.* from the Indian Institute of Technology Madras presented the *Acutus* [52] (Fig. 12), which is a morphable hybrid quadrotor and underwater vehicle robot. Unlike earlier quadrotor-like prototypes, the quadrotor components of the *Acutus* can be retracted upon transition to water, morphing into a streamlined vehicle propelled by a separate aquatic thruster and controlled using control surfaces similar to standard autonomous underwater vehicles (AUVs).

4.4. *Biologically inspired vehicles*

Besides solutions that are based on established aerial platforms, some developments of such experimental multimodal robots also take inspiration from nature and existing bio-mechanisms. There exist several examples of aerial–aquatic multimodal locomotion in animals ranging from the flying fish to flying squid [23]. In analyzing the force production of animals in different mediums, Maia *et al.* [39] summarize that in animals which have hybrid multimodal capabilities such as aquatic birds and flying fish, one mode is usually predominant and while the animal might have developed some mechanism to function in the second mode, it is always less developed than the dominant function. This is in line with the observations from existing aerial–aquatic vehicles, most commonly demonstrated by the partial-feature prototypes which are designed for a particular purpose and full-featured prototypes which do not have the same degree of mobility in water as they do in air.

Just like how ornithopters are often analyzed in aerial vehicle design, the most common source of bio-inspiration for aerial–aquatic vehicles is also the use of flapping wings as a propulsion and lift generation mechanism. While fixed wing and multirotor-based vehicles mostly utilize propeller thrusters, the use of flapping wings has long been hypothesized as being more energy efficient. Flapping wings are also potentially more adaptable for multimodal use as aerial propellers which typically spin at high rotational speeds face drastically different torque requirements when working underwater. In 2010, Lock *et al.* [53, 54] analyzed the numerical model of a wing inspired by the common guillemot in both aerial and aquatic locomotion. The authors verified the various effects of the different flapping techniques adopted by these birds in air and water and concluded that the retracted wing formation used in water offered significant power savings. A flapping wing actuation system (Fig. 13) meant for operation in both air and water was presented by Izraelevitz *et al.* [55] in 2015. By enabling three-dimensional rotation at the wing root, the proposed mechanism can produce both lift and thrust through different flapping regimes.

In 2015, the *RoboBee* [56] (Fig. 14) from Harvard University demonstrated an insect-scale aerial–aquatic vehicle that operates using flapping wings for both aerial and aquatic propulsion. This vehicle is based on the earlier work [57], which developed the piezoelectric flapping wing

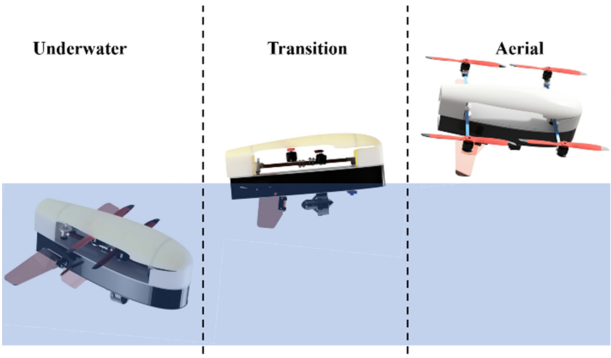


Fig. 12. The proposed operation modes of the Acutus from the Indian Institute of Technology Madras. Image reproduced with permission from [52], courtesy of the authors and publishers.

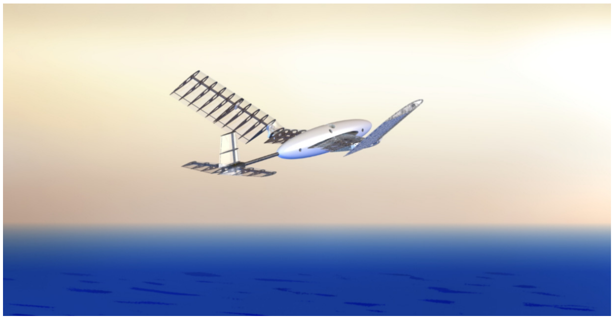


Fig. 13. The dual aerial/aquatic flapping vehicle concept from Massachusetts Institute of Technology. Image reproduced with permission from [55], courtesy of the authors and publishers.

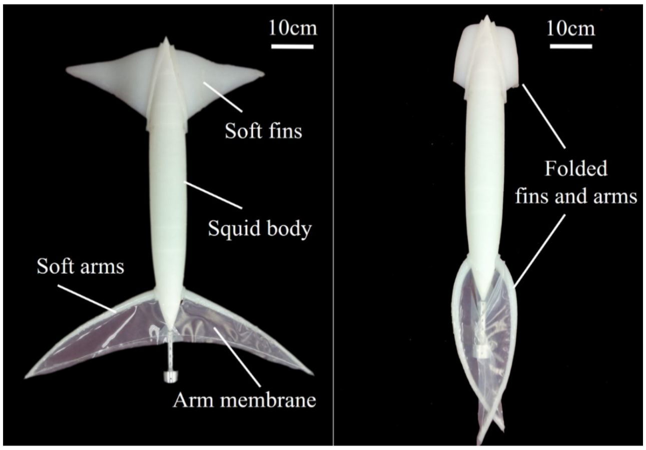
(a) (b)

Fig. 14. (a) The initial and (b) improved RoboBee prototype from Harvard University. Image reproduced with permission from [58], courtesy of the authors and publishers.

mechanism, and is the first insect scale aerial–aquatic vehicle of any form. By analyzing the fluid mechanics of the flapping wing in both air and water, the authors derived a flapping scheme that allows the same wing mechanism to propel the *RoboBee* in both air and water. The prototype was further improved in [58], where the authors solve the problem of significant interface surface tension during medium transition using oxyhydrogen, which is produced using electrolytic plates, that is ignited to create a launching impulse. Although the robot is able to launch itself out of the water, it is unable to regain flight upon water exit. Further development of the *RoboBee* platform in [59, 60] focused on achieving controlled untethered flight of the vehicle.

Besides flapping wings, the use of soft flappable fins for aquatic motion has also been investigated as a potential solution. In 2015, the US Naval Research Laboratory presented the *Flimmer* [61], which is a fixed wing-based vehicle with soft deformable fins capable of undulatory motion for propulsion and control underwater. These fins also double as control surfaces in aerial operation.

In 2019, Hou *et al.* [62] from Beihang University presented a squid-like aerial–aquatic vehicle with pneumatically driven morphing fins and arms (Fig. 15). The authors proposed that soft morphing structures can be used as an alternative to adapt to multimodal locomotion. The prototype is jet propelled in water, and although wind and water tunnel tests were performed, aerial experiments were not demonstrated and the design is inherently not meant for sustained aerial flight. Similarly, Zufferey *et al.* [63] also proposed the use of a multiple-use water jet thruster inspired by the flying squid combined with a winged glider vehicle (Fig. 16) inspired by the flying fish. Combined, the water jet that is produced explosively through combustion of solid reactants can be used to repeatedly launch the glider out of the water surface to overcome obstacles. The flying fish was also the inspiration for the *Robotic Flying Fish* [64] (Fig. 17) designed by students from Franklin W. Olin College of Engineering. Although the prototype presented was meant to mimic the undulatory motion of the



(a) (b)

Fig. 15. Prototype of the squid-like aerial–aquatic vehicle with soft morphing structure in its (a) spread and (b) folded state. Image reproduced with permission from [62], courtesy of the authors and publishers.

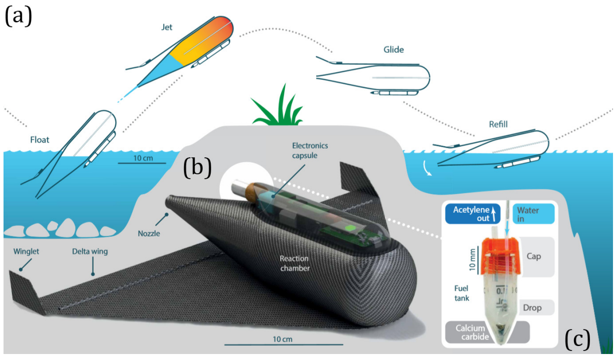


Fig. 16. Prototype of the water jet launched glider from Imperial College London. Image reproduced with permission from [63], courtesy of the authors and publishers.

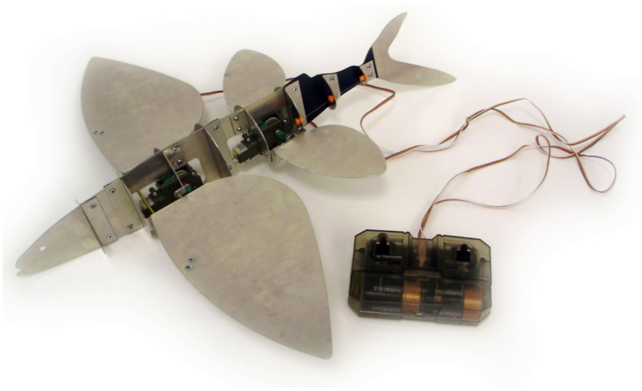


Fig. 17. The robotic flying fish prototype from Franklin W. Olin College of Engineering. Image reproduced with permission from [64], courtesy of the authors and publishers.

flying fish's tail to propel the vehicle on the surface, no experimental details were shown to verify its functionality.

5. Analysis of Aerial–Aquatic Functionality

Despite the many solutions that have been presented and proposed, several are either conceptual or simulation-based, and a large number have only demonstrated partial aerial–aquatic features, either by design or because they are still in the early developmental phase. The reasons for the limited functionality vary, but the fact remains that the difficulties of creating a truly multimodal aerial–aquatic vehicle as described in Sec. 3 have resulted in only a handful of full-feature working prototypes thus far.

In this section, we will analyze the various solutions that have been adopted by existing aerial–aquatic prototypes with regard to the four primary stages that make up a basic mission profile of a full-featured aerial–aquatic vehicle:

(i) Aerial flight
(ii) Aquatic locomotion
(iii) Water entry (air-to-water transition)
(iv) Water exit (water-to-air transition)

In particular, we will focus the discussion on the feasibility and functionality of various approaches in a full-feature vehicle that can complete the above mission profile in a remotely controlled manner without external devices (such as separate launch vehicles) or significant human intervention beyond a single human operator. A summary of the full-featured aerial–aquatic prototypes that have been documented in literature thus far is shown in Table 2. Although many more prototypes described above are designed or proposed to have full aerial–aquatic function, this table only includes the examples that have demonstrated the full working function of the four stages on video or extensively documented in literature. It is also worth noting that unlike the prevalence and developed solutions for fully autonomous operations in UAVs and submersible vehicles, most of these working aerial–aquatic prototypes are manually controlled. As these vehicles are commonly based on established aerial platforms, their control methods are often similar to their aerial counterparts, and they either operate using the same principles and control system when submerged or switch to a standard submersible control system depending on the layout of the vehicle.

5.1. *Aerial flight*

Due to the demanding nature of lift generation in air in order to enable sustained aerial flight, almost all existing full-featured aerial–aquatic vehicles are based primarily on the well-established aerial platforms of either the fixed wing plane or multirotor. In many of these cases, the aerial function of the aerial–aquatic vehicle is identical to its exclusively aerial equivalent, with additional mechanisms for the aquatic phase of the mission, such as floodable wing compartments in [29–31] and the active buoyancy control device in [43], being carried as standard payload in aerial flight, which does not affect the primary structure of the aerial vehicle. Even in prototypes which feature morphable adaptive structures or designs in the hardware, such as foldable wings in [28] and the rotation of thrusters in [44–46], these are only activated after the transition to aquatic mode, and the vehicle structure in aerial mode remains identical to that of established aerial platforms. Therefore, besides the weight penalty of adaptive mechanisms or unused aquatic propulsors that have to be carried in flight, the aerial flight performance of these multimodal vehicles are often comparable to their exclusively aerial counterparts since their fundamental structure is the same.

5.2. *Aquatic locomotion*

Most of the existing aerial–aquatic vehicles discussed above are based primarily on aerial vehicles and have identical hardware layouts to established aerial platforms such as fixed wing planes and multirotors. Although this is a popular design paradigm due to the highly demanding nature of aerial flight, it inherently implies that the aquatic operation of the vehicle is secondary in terms of design considerations and is hence often compromised. Even though vehicular movement and control in water may appear more forgiving in terms of maintaining attitude stability due to the higher density and viscosity of the medium providing a damping effect on the vehicle, the dynamics in water can be more complicated than in air due to both the increase in fluid resistance and the presence of buoyancy. As such, the physical challenges of being submerged such as static stability and locomotion methods should be considered as part of the vehicle's primary design in addition to the basic propulsive efficiency.

5.2.1. *Buoyancy management*

For any submerged vehicle, the net buoyancy force is a significant design parameter as a large positive buoyancy would make diving difficult and inefficient as large amounts of active thrust would be needed to counter it. Ideally, an underwater vehicle should be of neutral buoyancy so that no extra force is required to hold its depth at any position. For aerial–aquatic vehicles, the lightweight requirements of aerial flight often imply that the overall vehicle is of relatively low density and hence likely to be positively buoyant.

Table 2. Summary of aerial-aquatic prototypes that have been documented as having demonstrated full multimodal function experimentally.

Year	Vehicle	Organization	Type	Aerial function	Aquatic function	Water entry method	Water exit method	Notes	Sources
2015	Naviator	Rutgers University	X8-Octorotor	Multirotor	Multirotor	Vertical landing	Vertical take-off	—	[39, 40]
2016	LoonCopter	Oakland University	Quadrotor	Multirotor	Multirotor (rotated)	Vertical landing	Vertical take-off	Buoyancy control that adjusts orientation underwater.	[43]
2017	Eagleray XAV	North Carolina State University/ Teledyne	Fixed wing	Fixed wing	Fixed wing	Surface landing	Vertical take-off	Floodable wing compartments.	[29]
2018	Seabird-inspired UAV-UUV	North Carolina State University/ Teledyne	Fixed wing	Fixed wing	Fixed wing	Surface landing	Vertical take-off	Floodable wing compartments, separate aquatic propeller.	[30]
2018	Flying Fish (APL)	John Hopkins University Applied Physics Lab	Fixed wing (Delta wing)	Fixed wing	Fixed wing	Plunge diving	Inclined take-off	—	[32, 33]
2019	NEZHA	Shanghai Jiaotong University	Hybrid	VTOL/ Forward cruise	Underwater glider	Vertical landing	Vertical take-off	Able to function as a quadrotor with horizontal cruise flight mode in air.	[50, 51]
2019	Morphable Hybrid Quadrotor	National University of Singapore	Quadrotor	Multirotor	Vectored thrust	Vertical landing	Vertical take-off	Vectored thrust in aquatic mode through rotation of thrusters about arm axes.	[44–46]

In order to overcome this, the existing aerial–aquatic prototypes commonly use one of the three solutions: active buoyancy control, passive buoyancy control, and pre-calibrated buoyancy.

The most effective method of controlling buoyancy is through an active buoyancy control system that ingests or expels water into internal reservoirs to adjust the net buoyancy of the vehicle. The advantage of this system is the ability to finely adjust to any differences in buoyancy since the system can be actively controlled. While this is a common feature in most underwater submersible vehicles, this solution is rarely adopted in aerial–aquatic vehicles due to the associate weight cost of carrying such a system onboard. An example of such active buoyancy control is demonstrated in the *Looncopter* [43], which uses the same mechanism to adjust the vehicle's buoyancy and center of gravity to obtain the desired default underwater attitude. The submersible flying boat prototype in [28] achieves a similar effect using valves and water inlets, though it is not designed to tune or alter the vehicle's buoyancy when in complete underwater motion. An alternative to ingesting water into the vehicle is to use a pneumatic buoyancy device, which is adopted in the *NEZHA* [51]. The prototype uses an external bladder that is inflated by onboard compressed air to alter it's buoyancy when operating in underwater glider mode. Yang *et al.* also proposed the use of inflatable balloons in [22] to adjust the position of the vehicle's center of buoyancy to achieve the desired water exit position.

Passive buoyancy control is mechanically much simpler as it involves the complete flooding of compartments in the vehicle through openings that allow passive water inflow. This is the approach taken in [29, 30], and the modeling of this passively flooding and draining mechanism is discussed in [31]. As the name suggests, passive buoyancy control does not allow active fine-tuning, and is in many ways, similar to pre-calibrated buoyancy as the flooding of compartments occurs naturally upon water entry to obtain the designed buoyancy characteristics. However, unlike pre-calibrated buoyancy, passive buoyancy control systems require draining to regain its original state after water exit.

The simplest method to manage the issue of excess buoyancy is to pre-calibrate the overall vehicle density to achieve the desired buoyancy properties, which is likely to be near neutral buoyancy. This differs from the passive buoyancy control method above as it does not involve any draining of flooded components upon water exit to restore the aerial state of the vehicle. As weight is a limiting design factor for aerial flight, the desired density is likely achieved through compact packaging. However, as this is fixed and determined upon the build of the vehicle, it is unable to adapt to aquatic environments of different densities. Nevertheless, this is a commonly adopted solution as seen in the prototypes in [38, 40, 24, 32, 45], as most of these research prototypes are small-scale vehicles and carrying any buoyancy devices would imply significant weight costs.

5.2.2. *Thruster efficiency*

While biologically inspired propulsion methods such as flapping wings have often been touted as potentially more energy efficient, the use of propeller-based thrusters remains significantly more prevalent in most aspects of aerial and aquatic robot designs as their mechanical simplicity and effectiveness are difficult to surpass.

As most proof-of-concept aerial–aquatic designs are small-scale vehicles, a common approach is to use the same set of aerial motors and propellers underwater. This option has the advantage of being direct, simple and relatively lightweight as it does not involve carrying a second set of propulsion system onboard. However, the drastically different medium properties of air and water have significant implications on the function of a motor-propeller system, especially an electrically powered one. The use of electric aerial propulsion systems directly under water was first investigated by Alzu'bi *et al.* [65] in 2015 through empirical tests, which showed that such systems can be run under water at very low speeds without cavitation. Subsequently, further investigations through both numerical simulation and experimental tests were conducted by Tan *et al.* [66] in 2017, where the authors conclude that the discrepancy in torque requirements between aerial and aquatic operation leads to an aerial motor-propeller system becoming heavily mismatched when used directly underwater. This results in very low efficiencies as the motor-propeller system is forced to operate at very low speeds that are far from its design point. It was also proposed in [66] that the torque mismatch of the system can be overcome by the addition of a two-mode gearbox controlled by the direction of the motor. Although a physical prototype of the miniature sized gearbox was presented and demonstrated to be feasible in [66], no existing full-feature vehicle has adopted such a solution. The off-design operation and motor-propeller matching were further investigated in [67], where the authors proposed an evaluation scheme to maximize the efficiency of such off-design systems through component selection and identifying the feasible operating range of the motor-propeller system when submerged.

Of the seven full-feature prototypes listed in Table 2, five use the same electric aerial thrusters directly underwater for propulsion. Of these, three are multirotor-type vehicles. The distributed nature of thrust generation in multirotors reduces the impact of this direct usage as the increase in fluid forces acting on the propellers is split among the multiple thrusters, reducing the torque and thrust demands on each propeller.

5.2.3. *Locomotion method*

Besides the absolute propulsive efficiency of the thrusters, the hardware configuration also has a significant impact on the effectiveness of locomotion underwater. This can be observed through the common thruster configurations that are adopted by established submersible vehicles. Thruster propelled underwater vehicles can be classified into two main categories: AUV-type, which are long slender torpedo shaped bodies with a single thruster; and ROV-type, which typically uses three or more thrusters oriented in different axes to provide direct actuation.

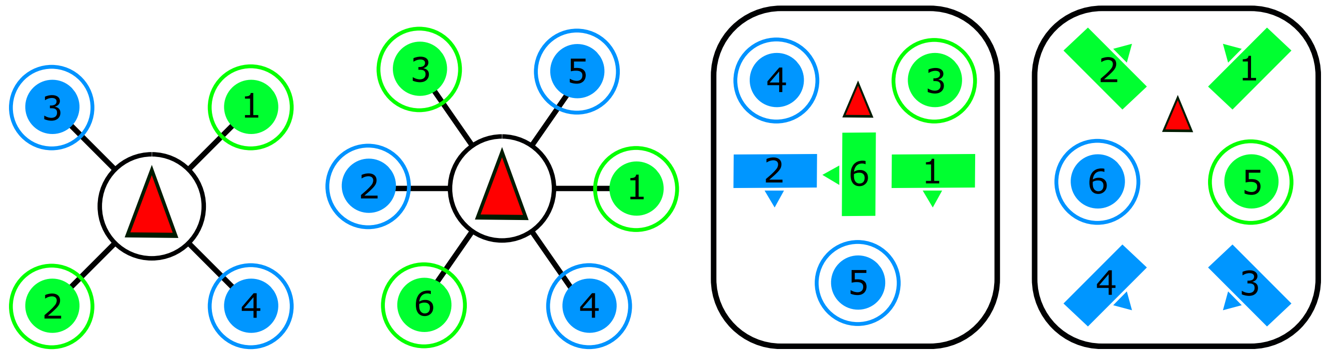
The hardware layout and locomotion method of fixed wing planes are similar to that of AUVs, using a single thruster to provide forwards thrust while using control surfaces to produce roll, pitch and yaw movements. As such, the aerial–aquatic prototypes that are based on such fixed wing structures can operate directly when submerged using the same principles. This has been demonstrated in [29, 30, 32]. Although the wings of all three prototypes were not designed to be streamlined or optimized for underwater motion, the buoyancy adaptations adopted and the relatively slower motion underwater result in this not having prohibitively negative impact on the underwater locomotion of the vehicle.

On the other hand, there are significant design differences in the thruster layouts of ROVs as compared with its aerial equivalent, multirotors, as shown in Fig. 18. While aerial multirotors direct all of their thrusters in the vertical direction to generate lift directly, ROVs typically direct their thrusters in all axes, with most acting in the lateral plane. With the presence of buoyancy underwater, there is less need in providing thrust in the vertical direction. Conversely, the larger resistance forces experienced in water increase the need for thrusters to act directly in the direction of motion, namely the surge, sway, and heave directions. This is also significantly different from the operating principles of multirotors, which use rotational accelerations in roll and pitch to direct a small component of thrust in sway and surge, respectively.

The implications of these differences can be seen in the underwater locomotion methods of the multirotor-based full-feature prototypes. Due to the higher fluid resistance in water, the *Naviator* [39, 40] has to pitch at a large angle to direct a larger component of thrust in the surge direction in order to move forward. When the thrusters are not activated, the vehicle reverts to the default orientation of thrusters pointing upwards, causing movement in water to be relatively tedious due to the extensive rotational motions that are needed to move in the lateral directions. To control the vehicle in this mode, the authors used a singularity free quaternion-based representation [68]. The *Looncopter* [43] improves on this by adjusting the default position of the multirotor to be rotated perpendicularly so that forward movement can be actuated directly. Instead of rotating the entire vehicle, the *Morphable Hybrid Quadrotor* [45] adopts a different approach to this problem by rotating the individual thrusters to point in the lateral or vertically downwards directions (Fig. 19). This would allow the vehicle to execute a vertical dive without rotation of the body axes, which is not possible in a fixed aerial thruster layout. Although the rotation of the thrusters aligns the layout closer to that of an ROV, it is still fundamentally different as typical aquatic thrusters are bidirectional, and the aerial thrusters used in [45] spin in only one direction, limiting the number of thrusters that can be used to propel the vehicle in each lateral direction.

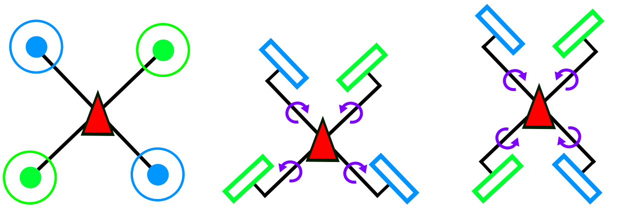
5.3. *Water entry*

The transition from air to water is relatively straightforward as it is possible to do this by directly landing or



(a) Quadrotor X (b) Hexarotor X (c) 6DOF ROV (d) Vectored ROV

Fig. 18. (a) and (b) are examples of typical thruster layouts for aerial multirotors and (c) and (d) are typical layouts of underwater ROVs. Green indicates a counter-clockwise rotating thruster while blue represents a clockwise rotating thruster. Image reproduced with permission from [44], courtesy of the authors and publishers.



(a) Aerial (b) Tilted-Forward (c) Tilted-Balanced

Fig. 19. The direction of tilt showing the resulting configuration (c) adopted by the morphable hybrid quadrotor. Image reproduced with permission from [44], courtesy of the authors and publishers.

dropping into the target water body as long as the vehicle can withstand the impact. This trivial case of landing on the water surface can be further classified into vertical landing and runway landing. For all multirotor-based prototypes, the water entry transition is a simple vertical landing on the water surface, just like a standard landing on ground. As most of these vehicles are typically buoyant, floating on the surface allows the vehicle to activate any transition devices that are meant for aquatic motion such as buoyancy control devices. Fixed wing-based vehicles can also drop directly into the water body, though their larger footprint will require more care to be taken to ensure that the vehicle can withstand the impact. The alternative of a runway landing on the water surface for fixed wing vehicles acts similarly, though [29] indicates that a slight flare is required to achieve a desirable water entry orientation of the vehicle. The accelerations experienced by the vehicle upon water impact was also found to be large, with an average *g*-loading of 8.4 g, resulting in structural damage if the landing was not controlled within the ideal angle.

To maximize the effectiveness of water entry and translate some of the kinetic energy into diving depth, plunge diving has often been suggested as a feature and mode of water entry. Inspired by the behavior of gannets and other seabirds, this method involves streamlining the vehicle, commonly through sweeping back its wings, before diving head-first into the water at high speeds so that the momentum from the drop is carried into the water and translated into depth. Although this method has been frequently studied in many early partial-feature prototypes such as [18–21, 24], most existing fixed-wing type full-feature prototypes adopt the runway landing instead. Although the runway landing requires an extended area to perform, this is often available as the outdoor conditions which these prototypes are built for typically involve larger water bodies as opposed to narrow, constrained ones. In addition, even though runway landings theoretically require calm surface conditions to execute as opposed to plunge diving which is less affected by rough waters, the ability to make a perfect runway landing is relatively irrelevant for a full-feature vehicle as it is able to re-orient and continue the aquatic phase of its mission regardless of its landing pose as long as it can withstand the impact. Being the only full-feature prototype to adopt a plunge diving-type water entry method, the *Flying Fish (APL)* [32] is less similar to the above studies on streamlined plunge diving to maximize dive depth and more aligned to a general direct water entry. Although the water entry process was not described in detail in [32], it differs from the general concept of plunge diving as the triangular wing and propeller are not collapsible and maximizing dive depth was not a design consideration.

5.4. *Water exit*

The transition from water to air is theoretically much more complicated than water entry due to the higher environmental drag on the vehicle when submerged and the need to shed any water in contact with the vehicle while transitioning completely to aerial flight. As opposed to the presence of buoyancy upon water entry, the vehicle loses this additional force that counters weight and has to generate sufficient lift to successfully leave the water surface.

A specialized mechanism for water exit (Fig. 20) was proposed by Siddall *et al.* [23] in 2014. Inspired by the water jet streams of flying squids, the authors proposed the use of a water jet thruster to launch the vehicle out of the water at high speeds using compressed air carried on board. Although this method provides high power density and launching ability, the compressed gas tank on board only provides a single charge and hence the vehicle cannot repeatedly enter and exit the water using this mechanism. A similar prototype was also presented by Guo *et al.* in [69]. A consecutive-use variation of this idea was proposed by Zufferey *et al.* in [63] by using solid reactants to produce a combustible gas that is subsequently ignited to produce the launching force of the water jet.

Despite the demonstrated function of a water jet launch to allow a fast transition from water to air, all existing full-feature prototypes opted for more direct approaches to water exit. The multirotor-based vehicles all transition from water to air through a direct vertical take-off from the water surface. Maia *et al.* proposed in [39] that by using an X8-octorotor configuration, which has two layers of four thrusters each on top of each other, at least one set of four thrusters will be in the same medium at any point in the transition. This will allow consistent thrusting force for the water to air transition. The vertical take-off procedure can be further simplified if the vehicle is positively buoyant such that the propellers are clear of the water surface, as in [43], in which case taking off directly from the water surface is no different from taking off from land. In fact, a simple quadrotor with its propellers beneath the water surface is able to breach the water surface and transition directly

(a) (b)

Fig. 20. (a) The AquaMAV prototype demonstrating its water jet launch; and (b) a timelapse of the launch trajectory. Images reproduced with permission from [24], courtesy of the authors and publishers.

from water to air as demonstrated by Zha *et al.* in [70]. This method was also adopted by the *Morphable Hybrid Quadrotor* in [45]. The direct vertical water exit approach is possible by maintaining the attitude of the multirotor through feedback so that the thrusters are consistently in-plane, and hence is effective only in relatively calm waters with little disturbance. The transition control of a hybrid multirotor vehicle with separate sets of aerial and aquatic propellers such as the *HUAUV* in [47, 48] was proposed by Ma *et al.* [71] although a working prototype of this design has yet to be documented.

The dynamics of a fixed wing-type vehicle leaving the water have been theoretically modeled in [72, 73]. Just like how multirotor-based vehicles perform direct vertical take-offs from the water surface, the existing full-feature fixed wing vehicles also perform water exit through a similar procedure. The prototypes in [29, 30] position the vehicle in a vertical nose-up orientation beneath the surface before using their single thruster to accelerate out of the water. The direct approach was also adopted by the prototype in [32], though it breaks the water surface at an inclined angle instead of vertically.

From these examples, we can see that a functional water exit strategy can be achieved rather directly as demonstrated in the full-feature prototypes that have been presented thus far. The strongest reason for the popular adoption of this approach is its relative simplicity as opposed to using other methods that would require extra components or mechanisms. The effectiveness of this method stems from the ability of the vehicle's thruster to produce thrust underwater. Given the higher density of water, there is significant thrust generated despite the lower rotational speeds of propellers. More importantly, by building up speed underwater, the time spent in the intermediate water–air interface can be relatively short and once the vehicle is past this phase the aerial thruster can regain its normal intended function and generate lift in its design condition. However, it should also be noted that for this to be possible, the designs presented have a large thrust-to-weight ratio of more than one, even for the fixed wing designs with a single propeller. Another limitation is that the direct water exit typically requires the water surface to be calm, as large disturbances would affect the critical attitude of the vehicle during the transition and prevent the thrusters from clearing the water effectively.

6. Conclusion

In this survey, we review the recent developments in the area of aerial–aquatic vehicles, which are multimodal vehicles that can operate in both air and water. Unlike earlier developments, recent prototypes have demonstrated much more complete multimodal function.

The progression of aerial–aquatic vehicles can be seen as the increasing aquatic functionality in such multimodal vehicles. Due to the contradictory nature of design goals in the two mediums and the more energy-demanding requirement of generating sufficient lift in air, most of the earliest aerial–aquatic vehicles are seaplane-type vehicles, which can come into contact with the water surface but are not typically submerged during its mission profile. This was subsequently extended such that the vehicles are adapted to withstand being submerged. Such examples include partial-function vehicles which use methods such as plunge diving to achieve depth for purposes such as water sample collection or submersible-launched aerial vehicles which are assisted to the water surface before performing standard aerial operation. Both of these examples are primarily passive in the aquatic phase, even though they can spend an extended amount of time underwater. The recent developments further expand the range of function for such aerial–aquatic vehicles in the aquatic phase by demonstrating full-featured mobile function. A range of different platforms, from fixed wings to multirotors, have been adapted such that they can be controlled and operated in water similar to how they work in air. Most recent developments further streamline such solutions by adopting hybrid or morphable structure to better adapt the vehicle for submerged movement and hence improving locomotive efficiency which has been a common shortcoming of early prototypes which use identical physical platforms in both mediums.

To summarize, aerial–aquatic vehicles have seen rapid developments in recent years, and the fundamental concept of a full-function multimodal robot that can work in both air and water has been realized in several proof-of-concept prototypes, which is a major breakthrough for this area. Although the fundamental design challenges limit the effectiveness of some solutions and forces necessary design trade-offs, often in the form of compromised efficiency in one or both mediums, an increasingly wide range of novel solutions have been proposed to overcome these challenges. While current working prototypes mostly adopt simple direct solutions to the challenges instead of more refined and specifically tailored mechanisms that have been proposed, the demonstrated functionality is an encouraging sign that a full-function aerial–aquatic vehicle is a feasible and realistic concept. For such vehicles to achieve autonomous operation, which is a common goal of unmanned vehicles, more work is still required in the development of specific technologies for modules including communications and control, which currently rely on simple combinations of existing solutions. With further developments on the various solutions, there is likely to be a large potential for growth in the functionality and usage of these vehicles.

Acknowledgments

The work of Ben M. Chen is supported in part by the Key Program of the National Natural Science Foundation of China (Grant No. U1613225), and in part by Peng Cheng Laboratory.

References

[1] Unknown, Denmark's amazing submarine plane, *Mod. Mech. Invent.* (1930) 74–75.
[2] G. Petrov, *Flying Submarine* (2013).
[3] *Cormorant Unmanned Air Vehicle (UAV)* (2006).
[4] B. Sweetman, The Navy's swimming spy plane, *Popular Sci.* **268**(3) (2006) 56–57.
[5] X. Yang, T. Wang, J. Liang, G. Yao and M. Liu, Survey on the novel hybrid aquatic-aerial amphibious aircraft: Aquatic unmanned aerial vehicle (AquaUAV), *Prog. Aerospace Sci.* **74** (2015) 131–151.
[6] S. Qiu and W. Cui, An overview on aquatic unmanned aerial vehicles, *Ann. Rev. Res.* **5**(3) (2019) 10–28.
[7] J.-P. Ore, S. Elbaum, A. Burgin and C. Detweiler, Autonomous aerial water sampling, *J. Field Robot.* **32**(8) (2015) 1095–1113.
[8] R. R. Murphy, E. Steimle, C. Griffin, C. Cullins, M. Hall and K. Pratt, Cooperative use of unmanned sea surface and micro aerial vehicles at Hurricane Wilma, *J. Field Robot.* **25**(3) (2008) 164–180.
[9] R. R. Murphy, K. L. Dreger, S. Newsome, J. Rodocker, B. Slaughter, R. Smith, E. Steimle, T. Kimura, K. Makabe, K. Kon, H. Mizumoto, M. Hatayama, F. Matsuno, S. Tadokoro and O. Kawase, Marine heterogeneous multirobot systems at the great Eastern Japan Tsunami recovery, *J. Field Robot.* **29**(5) (2012) 819–831.
[10] K. Nagatani, S. Kiribayashi, Y. Okada, K. Otake, K. Yoshida, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi, M. Fukushima and S. Kawatsuma, Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots, *J. Field Robot.* **30**(1) (2013) 44–63.
[11] Y. Wu, Coordinated path planning for an unmanned aerial-aquatic vehicle (UAAV) and an autonomous underwater vehicle (AUV) in an underwater target strike mission, *Ocean Eng.* **182** (2019) 162–173.
[12] Y. Wu, L. Li, X. Su and J. Cui, Multi-phase trajectory optimization for an aerial-aquatic vehicle considering the influence of navigation error, *Eng. Appl. Artif. Intell.* **89** (2020).
[13] R.-A. Peloquin, D. Thibault and A. L. Desbiens, Design of a passive vertical takeoff and landing aquatic UAV, *IEEE Robot. Autom. Lett.* **2** (2) (2017) 381–388.
[14] R. Zufferey, A. O. Ancel, C. Raposo, S. F. Armanini, A. Farinha, R. Siddall, I. Berasaluce, H. Zhu and M. Kovac, SailMAV: Design and implementation of a novel multi-modal flying sailing robot, *IEEE Robot. Autom. Lett.* **4**(3) (2019) 2894–2901.
[15] D. Parry, Navy launches UAV from submerged submarine, *US Naval Research Laboratory News Release* (2013).
[16] J. Bingham, DSEI 2017: Lockheed Martin launches Outrider UAV, *Jane's Int. Defence Rev.* (2017).
[17] D. Szondy, Lockheed Martin unpacks foldable Outrider canister drone, *New Atlas* (2017).
[18] A. Fabian, Y. Feng, E. Swartz, D. Thurmer and R. Wang, *Hybrid Aerial Underwater Vehicle* (MIT Lincoln Lab, 2012).
[19] J. Liang, X. Yang, T. Wang, G. Yao and W. Zhao, Design and experiment of a bionic gannet for plunge-diving, *J. Bionic Eng.* **10**(3) (2013) 282–291.
[20] X. Yang, J. Liang, T. Wang, G. Yao, W. Zhao, Y. Zhang and C. Han, Computational simulation of a submersible unmanned aerial vehicle impacting with water, *2013 IEEE Int. Conf. Robotics and Biomimetics, ROBIO 2013* (IEEE, 2013), pp. 1138–1143.
[21] T. M. Wang, X. B. Yang, J. H. Liang, G. C. Yao and W. D. Zhao, CFD based investigation on the impact acceleration when a gannet impacts with water during plunge diving, *Bioinspir. Biomimet.* **8**(3) (2013).
[22] X. Yang, T. Wang, J. Liang, G. Yao and W. Zhao, Submersible unmanned aerial vehicle concept design study, *2013 Aviation Technology, Integration, and Operations Conf.* (American Institute of Aeronautics and Astronautics, Reston, Virginia, 2013).
[23] R. Siddall and M. Kovač, Launching the AquaMAV: Bioinspired design for aerial-aquatic robotic platforms, *Bioinspir. Biomimet.* **9**(3) (2014).
[24] R. Siddall, A. Ortega Ancel and M. Kovač, Wind and water tunnel testing of a morphing aquatic micro air vehicle, *Interface Focus* **7**(1) (2017).
[25] R. J. D. Siddall, *Aerial Aquatic Locomotion With Miniature Robots* (2018).
[26] R. Siddall and M. Kovac, A water jet thruster for an aquatic micro air vehicle, *2015 IEEE Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2015), pp. 3979–3985.
[27] R. Siddall and M. Kovac, Fast aquatic escape with a jet thruster, *IEEE/ASME Trans. Mechatron.* **22**(1) (2017) 217–226.
[28] G. Yao, J. Liang, T. Wang, X. Yang, M. Liu and Y. Zhang, Submersible unmanned flying boat: Design and experiment, *2014 IEEE Int. Conf. Robotics and Biomimetics (ROBIO 2014)* (IEEE, 2014), pp. 1308–1313.

[29] W. Weisler, W. Stewart, M. B. Anderson, K. J. Peters, A. Gopalarathnam and M. Bryant, Testing and characterization of a fixed wing cross-domain unmanned vehicle operating in aerial and underwater environments, *IEEE J. Ocean. Eng.* **43**(4) (2018) 969–982.

[30] W. Stewart, W. Weisler, M. MacLeod, T. Powers, A. Defreitas, R. Gritter, M. Anderson, K. Peters, A. Gopalarathnam and M. Bryant, Design and demonstration of a seabird-inspired fixed-wing hybrid UAV-UUV system, *Bioinspir. Biomimet.* **13**(5) (2018).

[31] W. Stewart, W. Weisler, M. Anderson, M. Bryant and K. Peters, Dynamic modeling of passively draining structures for aerial-aquatic unmanned vehicles, *IEEE J. Ocean. Eng.* **45** (2020) 840–850.

[32] J. Moore, A. Fein and W. Setzler, Design and analysis of a fixed-wing unmanned aerial-aquatic vehicle, *2018 IEEE Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2018), pp. 1236–1243.

[33] J. Moore, Closed-loop control of a delta-wing unmanned aerial-aquatic vehicle (2019).

[34] P. Rodrigues, F. Marques, E. Pinto, R. Pombeiro, A. Lourenco, R. Mendonca, P. Santana and J. Barata, An open-source watertight unmanned aerial vehicle for water quality monitoring, *OCEANS 2015 – MTS/IEEE Washington* (IEEE, 2015).

[35] *SwellPro Waterproof Drones* (2018).

[36] *QuadH2O - Waterproof Multirotors* (2020).

[37] B. Coxworth, Amphibious HexH2o drone shoots both aerial and underwater video, *New Atlas* (2014).

[38] G. Brown, New UAV can launch from underwater for aerial missions, *John Hopkins Appl. Phys. Lab.* (2016).

[39] M. M. Maia, P. Soni and F. J. Diez-Garias, Demonstration of an aerial and submersible vehicle capable of flight and underwater navigation with seamless air-water transition (2015).

[40] M. M. Maia, D. A. Mercado and F. J. Diez, Design and implementation of multirotor aerial-underwater vehicles with experimental results, *2017 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (IEEE, 2017), pp. 961–966.

[41] D. A. Mercado, M. M. Maia and F. J. Diez, Aerial-underwater systems, a new paradigm in unmanned vehicles, *2017 Int. Conf. Unmanned Aircraft Systems (ICUAS)* (IEEE, 2017), pp. 1690–1695.

[42] D. A. Mercado Ravell, M. M. Maia and F. J. Diez, Modeling and control of unmanned aerial/underwater vehicles using hybrid control, *Control Eng. Practice* **76** (2018) 112–122.

[43] H. Alzu'bi, I. Mansour and O. Rawashdeh, Loon Copter: Implementation of a hybrid unmanned aquatic-aerial quadcopter with active buoyancy control, *J. Field Robot.* **35**(5) (2018) 764–778.

[44] Y. H. Tan and B. M. Chen, Design of a morphable multirotor aerial-aquatic vehicle, *OCEANS 2019 MTS/IEEE Seattle* (IEEE, 2019).

[45] Y. H. Tan and B. M. Chen, A morphable aerial-aquatic quadrotor with coupled symmetric thrust vectoring, *2020 IEEE Int. Conf. Robotics and Automation (ICRA)* (2020), pp. 2223–2229.

[46] Y. H. Tan and B. M. Chen, Thruster allocation and mapping of aerial and aquatic modes for a morphable multimodal quadrotor, *IEEE/ASME Trans. Mech.* (2020).

[47] P. L. J. Drews, A. A. Neto and M. F. M. Campos, Hybrid unmanned aerial underwater vehicle: Modeling and simulation, *2014 IEEE/RSJ Int. Conf. Intelligent Robots and Systems* (IEEE, 2014), pp. 4637–4642.

[48] A. A. Neto, L. A. Mozelli, P. L. J. Drews and M. F. M. Campos, Attitude control for an hybrid unmanned aerial underwater vehicle: A robust switched strategy with global stability, *2015 IEEE Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2015), pp. 395–400.

[49] A. C. Horn, P. M. Pinheiro, C. B. Silva, A. A. Neto and P. L. J. Drews-Jr, A study on configuration of propellers for multirotor-like hybrid aerial-aquatic vehicles, *2019 19th Int. Conf. Advanced Robotics (ICAR)* (IEEE, 2019), pp. 173–178.

[50] D. Lu, C. Xiong, B. Lyu, Z. Zeng and L. Lian, Multi-mode hybrid aerial underwater vehicle with extended endurance, *2018 OCEANS – MTS/IEEE Kobe Techno-Oceans (OTO)* (IEEE, 2018).

[51] D. Lu, C. Xiong, Z. Zeng and L. Lian, A multimodal aerial underwater vehicle with extended endurance and capabilities, *2019 Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2019), pp. 4674–4680.

[52] A. Vyas, R. Puppala, N. Sivadasan, A. Molawade, T. Ranganathan and A. Thondiyath, Modelling and dynamic analysis of a novel hybrid aerial-underwater robot – Acutus, *OCEANS 2019 – Marseille* (IEEE, 2019).

[53] R. J. Lock, R. Vaidyanathan, S. C. Burgess and J. Loveless, Development of a biologically inspired multi-modal wing model for aerial-aquatic robotic vehicles through empirical and numerical modelling of the common guillemot, Uria aalge, *Bioinspir. Biomimet.* **5**(4) (2010).

[54] R. J. Lock, *A Biologically-Inspired Multi-Modal Wing for Aerial-Aquatic Robotic Vehicles* (2011).

[55] J. S. Izraelevitz and M. S. Triantafyllou, A novel degree of freedom in flapping wings shows promise for a dual aerial/aquatic vehicle propulsor, *2015 IEEE Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2015), pp. 5830–5837.

[56] Y. Chen, E. F. Helbling, N. Gravish, K. Ma and R. J. Wood, Hybrid aerial and aquatic locomotion in an at-scale robotic insect, *2015 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (IEEE, 2015), pp. 331–338.

[57] K. Y. Ma, P. Chirarattananon, S. B. Fuller and R. J. Wood, Controlled flight of a biologically inspired, insect-scale robot, *Science* **340** (2013) 603–607.

[58] Y. Chen, H. Wang, E. F. Helbling, N. T. Jafferis, R. Zufferey, A. Ong, K. Ma, N. Gravish, P. Chirarattananon, M. Kovac and R. J. Wood, A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot, *Sci. Robot.* **2**(11) (2017).

[59] Y. Chen, H. Zhao, J. Mao, P. Chirarattananon, E. F. Helbling, N.-S. P. Hyun, D. R. Clarke and R. J. Wood, Controlled flight of a microrobot powered by soft artificial muscles, *Nature* **575** (2019) 324–329.

[60] N. T. Jafferis, E. F. Helbling, M. Karpelson and R. J. Wood, Untethered flight of an insect-sized flapping-wing microscale aerial vehicle, *Nature* **570** (2019) 491–495.

[61] D. Edwards, Flying-Swimmer (Flimmer) UAV/UUV, *US Naval Research Laboratory - LASR*.

[62] T. Hou, X. Yang, H. Su, B. Jiang, L. Chen, T. Wang and J. Liang, Design and experiments of a squid-like aquatic-aerial vehicle with soft morphing fins and arms, *2019 Int. Conf. Robotics and Automation (ICRA)* (IEEE, 2019), pp. 4681–4687.

[63] R. Zufferey, A. O. Ancel, A. Farinha, R. Siddall, S. F. Armanini, M. Nasr, R. V. Brahmal, G. Kennedy and M. Kovac, Consecutive aquatic jump-gliding with water-reactive fuel, *Sci. Robot.* **4**(34) (2019).

[64] R. Cherney, Robotic flying fish, Technical report, Franklin W. Olin College of Engineering (2010).

[65] H. Alzu'bi, O. Akinsanya, N. Kaja, I. Mansour and O. Rawashdeh, Evaluation of an aerial quadcopter power-plant for underwater operation, *2015 10th Int. Symp. Mechatronics and its Applications (ISMA)* (IEEE, 2015).

[66] Y. H. Tan, R. Siddall and M. Kovac, Efficient aerial-aquatic locomotion with a single propulsion system, *IEEE Robot. Autom. Lett.* **2**(3) (2017) 1304–1311.

[67] Y. H. Tan and B. M. Chen, Motor-propeller matching of aerial propulsion systems for direct aerial-aquatic operation, *2019 IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)* (IEEE, 2019), pp. 1963–1970.

[68] D. Mercado, M. Maia and F. J. Diez, Aerial-underwater systems, a new paradigm in unmanned vehicles, *J. Intell. Robot. Syst.* **95** (2019) 229–238.

[69] D. Guo, A. Bacciaglia, A. Ceruti, P. Marzocca and C. Bil, Design and development of a transition propulsion system for bimodal unmanned vehicles, *2018 Int. Conf. Unmanned Aircraft Systems (ICUAS)* (IEEE, 2018), pp. 549–558.

[70] J. Zha, E. Thacher, J. Kroeger, S. A. Makiharju and M. W. Mueller, Towards breaching a still water surface with a miniature unmanned

aerial underwater vehicle, *2019 Int. Conf. Unmanned Aircraft Systems (ICUAS)* (IEEE, 2019), pp. 1178–1185.

[71] Z. Ma, J. Feng and J. Yang, Research on vertical air-water transmedia control of hybrid unmanned aerial underwater vehicles based on adaptive sliding mode dynamical surface control, *Int. J. Adv. Robot. Syst.* **15**(2) (2018).

[72] D. Qi, J. Feng, B. Xu, A. Liu and Y. Li, Water exit model and takeoff control for a morphing cross-media vehicle, *J. Chin. Inst. Eng.* **40**(2) (2017) 110–117.

[73] J.-H. Hu, B.-W. Xu, J.-F. Feng, D. Qi, J. Yang and C. Wang, Research on water-exit and take-off process for morphing unmanned submersible aerial vehicle, *China Ocean Eng.* **31**(2) (2017) 202–209.

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