Adaptive Morphology in Aerial-Aquatic Robots

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1 Aerial-Aquatic Mobility

Aerial-aquatic mobility is envisaged to significantly facilitate applications involving aquatic sampling or underwater surveying. Allowing water vehicles to take flight would allow for rapid deployment, access to remote areas, overflying of obstacles and easy transitioning between separate bodies of water. The use of a single vehicle capable of reaching distant locations rapidly, conducting measurements and returning to base, would greatly improve upon the current solutions, which often involve integrating different types of vehicles (e.g. vessels carrying deployable submarines), or rely heavily on manpower (e.g. sensors deployed manually from ships) [1,2]. The usage of single adaptive multi-modal robots for such applications could significantly improve the efficiency, costs and safety of such operations.

1.1 Challenges

Aerial-aquatic robots are challenging to develop due to the conflicting requirements inherent to their different mission stages. Locomotion in different media is the source of many trade-offs. In fact, the Reynolds number increases more than tenfold from air to water, thus, efficient locomotion cannot be achieved using a conventional system. Instead, new propulsion systems and control approaches are necessary. Propulsion systems developed for air, for instance, are extremely inefficient in water and *vice versa*. Moreover, while lifting surfaces allow efficient locomotion in air, in water these impact performance due to the increased drag forces. Transition is also challenging because the impact with the water surface imposes strong loads on the structure. Air-water transition can be achieved either through a slow water surface approach, or through a higher-speed diving maneuver. Water to air transition is very power-intensive, [3,4] imposing either the usage of secondary dense energy sources for an impulsive transition, or the usage of horizontal speed and hydrodynamic lift for a controlled transition.

1.2 Aerial-aquatic mobility in nature and robotics

The vast majority of existing aerial-aquatic robots are non-adaptive configurations, i.e. they maintain the same structure and propulsive system for all modes of locomotion. Within this category, most robots are multi-rotor platforms [1, 5] and a small number are fixed-wing plat-

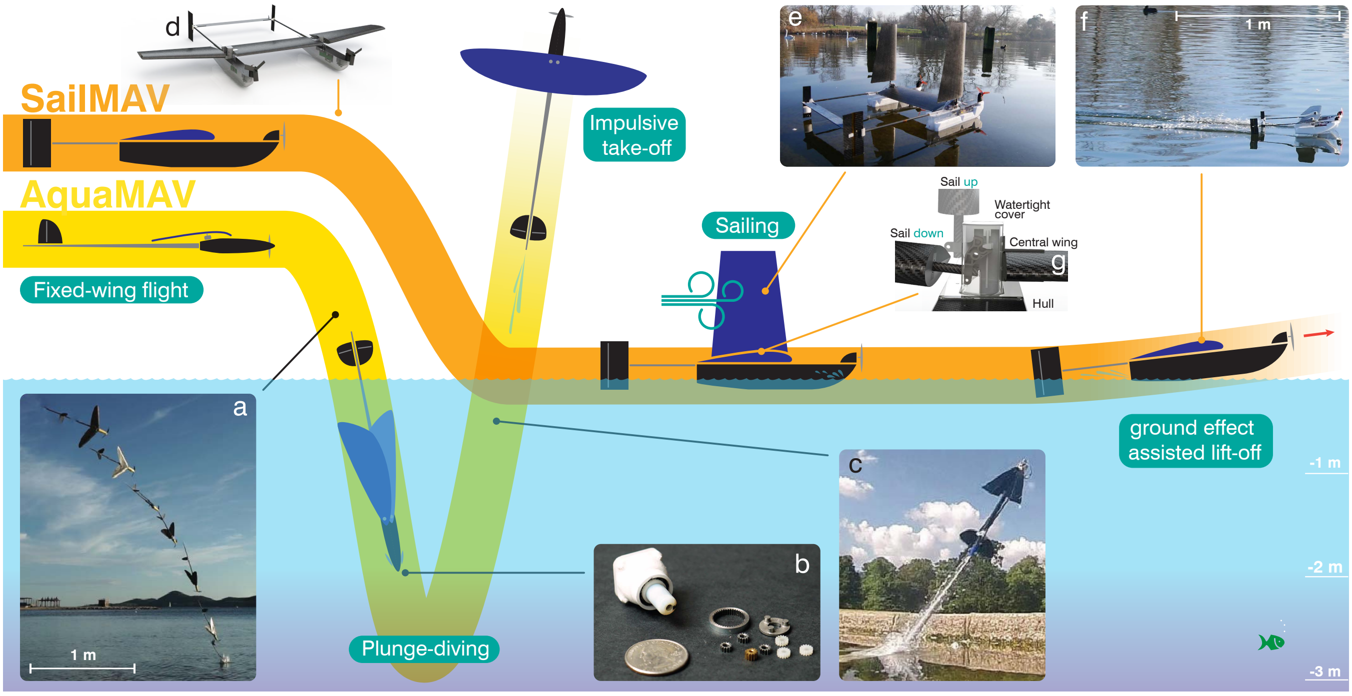

Figure 1: Adaptive wing morphing enabling robots to locomote in an aerial-aquatic environment. a) plunge-diving of the aquaMAV b) air-water gearbox c) Water escape via jetting d) SailMAV in flight e) Sailing mode f) Take-off g) folding mechanism.

forms [6, 7]. A bio-inspired alternative to achieve the flexibility to move in both media is structural adaptation. By changing its morphology, a robot can adjust to different environments, improving its performance throughout and attenuating the constraints linked to transition. This strategy is also widely used in nature. Diving birds, for instance, fold back their wings to reduce drag and limit water impact forces [2]. Flying fish extend their fins to improve their gliding performance [8], some spiders adapt their shape to sail [9], and mute swans have been observed to arch their wings to sail at speeds up to 1.3 m/s [10]. Two recently developed adaptive aerial-aquatic robots are presented in the remainder of this paper, where we discuss the design of each robot, as well as the advantages and limitations of adaptation for aerial-aquatic locomotion.

2 Wing Morphology Adaptation

The SailMAV flies as a fixed-wing platform (fig. 1.d) with a 0.9 m three-section wing and a flight range of 7 km. The carbon fibre asymmetric central wing provides high lift and stiffness, while the extremities (labeled as *sails*) have two degrees of freedom, i.e. angle of attack and folding angle. Once landed on the water surface, it leverages wind energy for passive locomotion (fig. 1.e). During this phase, the sails are in an upright position, locked in place by a custom-made folding mechanism (fig. 1.g). Sailing is autonomously handled by a modified flight controller [11]. By lowering the sails to a horizontal position, the SailMAV reverts to flight mode. At 3 m/s velocity, the robot begins to hydroplane thanks to specially designed hulls, at which point the drag decreases sharply. Take-off occurs at a low velocity through the help of ground effect (fig. 1.f).

The AquaMAV [2] employs a different aerial-aquatic locomotion approach, i.e. dynamic transition using a plunge-diving maneuver, which is less sensitive to the sea state compared to landing on the water surface. From the air, the two flat-plate wings fold back, initiating a dive. The robot hits the water nose first, with the propellers off and folded. The wing morphing reduces the impact forces on the robot and the drag in water, permitting a dive to several meters depth. An unactuated gearbox (fig. 1.b) reduces the rotation speed of the propeller to 1:15 [12], resulting in more effective underwater motion. The AquaMAV impulsively jets out of the water. At this stage, the wings are extended, and propelled flight carries the vehicle for up to 5 km.

The changing morphology allows both of these platforms to operate more efficiently. Wing morphing in the AquaMAV allows it to dive passively and reach a depth of 3 m, which, besides reducing drag in the water, saves redundant weight in flight, by not requiring a buoyancy control system. Moreover, the SailMAV's morphing wing allows it to fly without a fixed vertical sail, which would generate a large off-centred drag component and impact flight stability. Adaptive morphology brings substantial benefits in terms of weight, compared to single-configuration robots. Table 1 shows the penalty that the hybrid designs incurs. This was estimated by measuring individual component mass relevant to each mode. In addition, the hybrid design requires adaptations that impact performance. For the AquaMAV, for instance, a zero-thickness wing helps the robot to survive the plunge-dive and stay neutrally buoyant. For the SailMAV, a symmetric profile is used for the wings, to obtain the same behaviour when sailing under port or starboard wind. Both these design features necessary for in/on water operation lead to a reduced efficiency in flight.

Table 1: Measured redundant weight in air and water

Weight penalty	Water	Air
AquaMAV	29%	20%
SailMAV	20%	10%

3 Conclusion

This paper discusses possible structure morphology adaptation strategies that enable robots to overcome the challenges of aerial-aquatic locomotion. As an example, two vehicles are demonstrated, that employ widely different methods of adaptive morphology to provide, either wave-robustness and diving, or passive surface motion and multi-cycle mission capability. Future work will include the integration of custom and lightweight water samplers and sensors. Work is also necessary on the control of the vehicles for the execution of a full mission cycle autonomous.

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