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Review

Configuration Design and Trans-Media Control Status of the Hybrid Aerial Underwater Vehicles

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Abstract: Hybrid aerial underwater vehicles (HAUV) are newly borne vehicle concepts, which could fly in the air, navigate underwater, and cross the air-water surface repeatedly. Although there are many problems to be solved, the advanced concept, which combines the integrated multidomain locomotion of both water and air mediums is worth exploring. This paper presents the water–air trans-media status of the HAUV from the perspective of the configuration and trans-media control. It shows that the multi-rotor HAUV is relatively mature and has achieved a stable water–air trans-media process repeatedly. The morphing HAUV is still in its exploration stage, and has achieved partial success.

Keywords: morphing and multi-rotor HAUV; water-air multi-locomotion; trans-media control

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1. Introduction

With the rapid development of industrial technology, aerial unmanned vehicles (AUVs) and underwater autonomous vehicles (UAVs) complete various tasks, playing an important role in both civil and military fields. However, they are greatly limited by being unable to operate in air or in water. In view of "air–sea integration", a forward-looking concept of water–air hybrid aerial underwater vehicles (HAUVs) was suggested, which are also known as underwater-aerial cross-domain vehicles, water–air trans-media vehicles and water–air amphibious/aquatic vehicles. HAUVs were the deep integration of aviation and navigation technologies, which could break through the single medium limitation by operating both in air and underwater seamlessly. This is essentially different from both UAVs and AUVs, with the ability of rapid flight in the air and underwater stealth navigation. Although HAUVs are still in the stage of exploration research, they could be widely used in both civil and military fields to meet more diverse needs and higher-level requirements, as demonstrated in Yang [1], Alzu'Bi [2], and Kaja [3].

In the civil field, HAUVs could quickly fly to mission airspaces to collect aerial data, then submerge into water to collect underwater data, which could greatly improve a mission's efficiency. For example, HAUVs could be used for the detection of underwater pipeline leakages. Water surface and underwater detections are shown in Figure 1. In addition, they have unique advantages in terms of biological resource detection, port monitoring, chart drawing, seabed monitoring, meteorological detection, ecological environment detection, ecological observation, ship-bottom detection, offshore oil and gas-platform monitoring, pier detection, etc. [4].

In the military field, HAUVs integrate the advantages of rapid flight in the air with good underwater concealment [5,6]. They could make use of the physical separation of water and air mediums and realize long-distance concealed strikes by jumping between the water medium and the air medium. An imagined motion profile is presented in Figure 2. In addition, the emergence of HAUVs could ensure that military ships receive rapid support, playing an important role in the acquisition of information from the air and underwater.

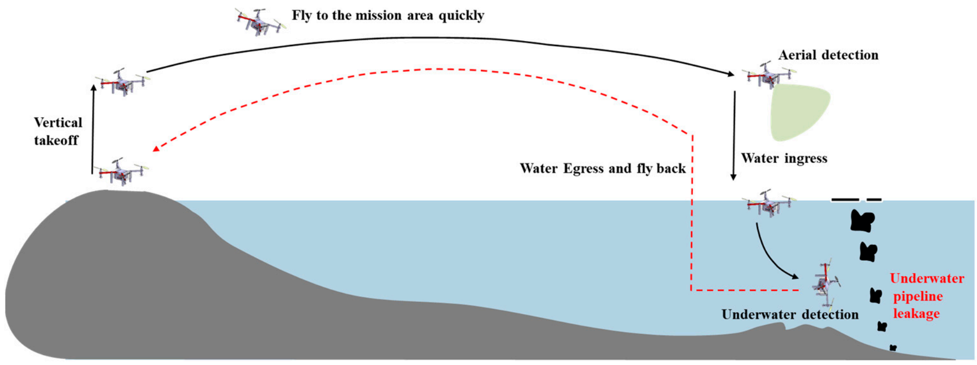


Figure 1. Water–air medium detections for underwater pipeline leakage.

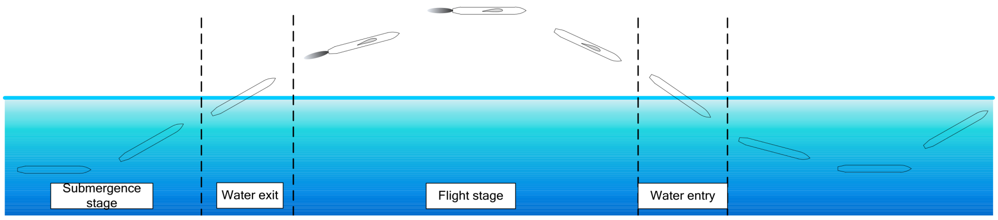


Figure 2. An imagined motion profile of an HAUV.

Although the prospects of this technology are bright, the development of HAUVs is also challenging due to two factors. First, the physical properties of water and air are very different, as shown in Table 1 adapted from [7]. As a result, it is difficult to accommodate the two mediums in the configuration design. Secondly, the research on HAUVs is multidisciplinary, involving aerodynamics, hydrodynamics, air flight control, and underwater navigation control. It increases the complexity of the development of control methods and motion dynamics. Overcoming these contradictions and solving these problems are the keys to the development of HAUVs. This paper draws conclusions on the configuration design and trans-media control issues. The authors expect that the comments made here could help in their development.

Table 1. Physical parameters of the 15 °C air and 20 °C water.

	Density (kg/m^3)	Dynamic Viscosity Coefficient (Pa·s)
Air	1.225	1.789×10^{-5}
Water	998.2	1.003×10^{-3}

2. Configuration Design

It is necessary for HAUVs to adapt to both the water and air mediums. This necessity creates unavoidable contradictions to the configuration design. Generally speaking, the design has obvious particularities in terms of weight matching, fuselage shape, wing layout, structural design, and power system. (a) In terms of the weight of the vehicle, the flight in the air should be as light as possible, and the underwater navigation should have considerable density and strength, which is conducive to diving. (b) Concerning fuselage shape, the different density increases the difficulty in configuration design. Based on the principle of Reynolds number similarity, there is a great difference in the speed of the same fuselage in water and air environments. (c) In the aspect of wing layout, the aircraft overcomes gravity by increasing the pressure difference between the upper and lower surfaces of the wings. When the velocity is constant, the wing area determines the lift. The submersibles can rise and dive by adjusting their own buoyancy. The wing surface is usually used to adjust the course and balance. In order to reduce the resistance of underwater navigation, the wing surface has a relatively short wingspan and a narrow chord. (d) In terms of structural design, underwater navigation has high requirements for both pressure and sealing. In flight, especially in low altitude flight, the sealing and pressure performance are hardly considered. Even the pressure hull used in high-altitude flight cannot be compared with the cabin in underwater navigation. In addition to this, the high-altitude flight requires overpressure in the cabin, while the submarine's skin is exposed to the inverse pressure: higher water pressure outside and lower air pressure inside. (e) In terms of the power system, the aero-engine relies heavily on air and cannot work underwater at present. The heavy underwater power system is also unsuitable for flight.

It is challenging that HAUVs should accommodate both the fluid inertia and drag encountered underwater without compromising the weight and lifting area requirements of flight. Ushakov and DARPA opened the prelude to the development of a manned HAUV, but these projects only demonstrated the preliminary design of the layout. Compared with a large-scale manned HAUV, researchers drew on the basic principles of bionics and turned their attention to a small-scale unmanned HAUV. Many animals, such as kingfishers, gannets, flying fish, and squid have the ability to cross the water–air surface [8–10]. The animals' habits aroused the researchers' interest, and they hoped to find the inspiration for the design of HAUVs from these animals. Two main kinds, multirotor HAUVs and morphing HAUVs, are being developed for the accommodation of air and water mediums.

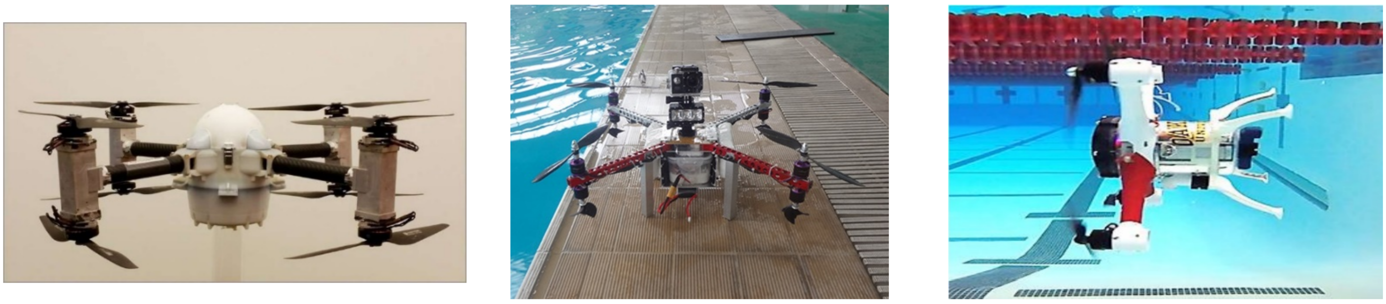
HAUVs that accomplish locomotion with changing air and underwater configurations could be defined as morphing HAUVs. Liang proposed a variable-sweep HAUV which could dive into the water like a gannet [11]. The vehicle was used to research water entry impact acceleration through falling down experiments. Kovac and Siddall further designed a variable-sweep HAUV, powered by a "squid spray" water jet thruster which was based on compressed carbon dioxide. It achieved the water-exit process experimentally [4,12]. More recently, the team designed a delta wing HAUV to improve flight stability after it left the water, as shown in Figure 3a [13]. These vehicles were designed to verify the feasibility of the jet thruster for inclined water exit, regardless of the whole water–air trans-media process of water exit, stability flight, water entry, and underwater navigation. The stored compressed air of the thruster could only achieve a single water-exit process. Stewart designed an amphibious vehicle which was driven by a high-power motor, as shown in Figure 3b, and completed the whole water–air trans-media process. It could only achieve vertical water exit, since the power came from a single air propeller. The next step was to research the design of the variable-sweep wing configuration, which could potentially decrease the water entry impact acceleration [14,15]. Similar prototypes were designed by Caruccio and Wang with detailed designs, fabrication, and testing presented in their literatures [16,17]. Guo proposed an interesting and perfect bimodal system, which consisted of a foldable blade propeller with a variable-sweep wing for aerial and underwater power and a compressed gas thruster for the egress process, as shown in Figure 3c [18]. The prototype was not manufactured. It was in the stage of conceptual design and experimental test for the bimodal system.

(**a**) (**b**) (**c**)

Figure 3. The morphing configuration of the HAUV. (**a**) Kovac's team; (**b**) Stewart's team; (**c**) Guo's team.

Compared with multi-rotor HAUVs, morphing HAUVs have the advantage of fast flight in air. However, the accommodation of the aerial and underwater movement efficiencies, as well as the water entry impact acceleration problem, are not being considered at present. Morphing HAUVs are at a very early stage where researchers are focused on the verification of the whole trans-media process with a manual remote-control mode. Nevertheless, it only achieved partial success in the whole trans-media process. At present, the vehicle is equipped with very little electronic equipment that would be susceptible to impact acceleration. In future, slow, vertical landings or the application of impact load-resistant electronic equipment could be considered as a solution to the impact load problem. A jet thruster could achieve a fast incline egress, while an air propeller could only achieve a vertical egress. Jet thruster power and variable-sweep configuration seem to be promising technical solutions.

In addition, multirotor HAUVs were designed and tested for multi-locomotion, benefiting from high maneuverability and hover capability. Neto proposed the first concept of a multirotor HAUV with four underwater propellers and four air propellers [19]. Following this, Maia [20], Feng [21], and Alzu'Bi [2] designed and manufactured multirotor HAUVs, as presented in Figure 4. They repeatedly completed the experimental verification of the air flight, underwater navigation, and vertical water–air multi-locomotion. Maia and Feng's HAUVs were neutrally buoyant with a dual-propeller system. A coaxial design was adopted, with Maia using eight of the same specially designed gas propellers for both air and water mediums, while Feng preferred four gas propellers and four water propellers. The dual-propeller system guaranteed seamless multi-locomotion with continuous aerial and underwater power. Alexandre also proposed an HAUV with four aquatic water and four aerial gas propellers [22]. Four aerial propellers were used both in air and underwater in Alzu'Bi's design. It floated on the surface of the water with a depth control system and then achieved flight. Furthermore, a student team proposed an amphibious collapsible helicopter called the Waterspout [23]. It would totally depend on buoyant force, ascending from a released point underwater to the water's surface. Lu attempted to develop an HAUV with four gas propellers and two fixed side wings to provide the lift necessary for flight and underwater gliding. Further to this, it could achieve three modes: forward-flight mode, VTOL mode for the water–air trans-media process, and underwater-glide mode [24]. It was therefore expected that this design would have better endurance.



(**a**) (**b**) (**c**)

Figure 4. The multirotor configuration of an HAUV. (**a**) Maia's team; (**b**) Feng's team; (**c**) Alzu'Bi's team.

In general, in benefiting from the hover capability, multirotor HAUVs have repeatedly realized successful multidomain locomotion, but the probability of a successful egress is low. Successful egress requires the remote-control operators to be well experienced. The optimized configuration design needs to improve the disturbance-rejection ability, and the efficiency of air–underwater movement needs further research.

3. Trans-Media Control

The process and control requirements of HAUVs are special and challenging for multidomain locomotion. As a combination of AUVs and UAVs, the control design of HUAVs could benefit from the control schemes of AUVs and UAVs. However, there are some differences in the design of control schemes between UAVs and AUVs. UAVs are generally designed to be neutrally stable that their buoyancy is equal to gravity. The angle of attack (AOA) is generally too small to prevent the shell from being damaged by excessive shear force during movement, and the design of hydrodynamic configuration is symmetrical, so the effect of lift is generally negligible. UAV requires the wing to generate lift to balance gravity. So, the range of AOA is also much bigger than that of AUV's. Therefore, in the process of controller design, the dynamic model of AUVs is generally expressed in the body's coordinate system, while the UAV is generally expressed in the velocity coordinate system, so as to make the expression of the dynamic equation more convenient for controller design. Then, the velocity, angular velocity, and Euler angle are selected as virtual control variables for the AUV, and the AOA, sideslip angle, and flight path angle could also be selected for the UAV, as presented in Figure 5 [25]. Combined with different control requirements, many linear and nonlinear control methods have been widely used to the control design of UAVs and AUVs, including fuzzy control [26,27], dynamic-inverse control [28], Lyapunov-based backstepping control [29–31], adaptive neural network control [32,33], sliding mode variable structure control [34], and so on. Benefiting from these methods, outstanding works were carried out to rectify the control issues of HAUVs.

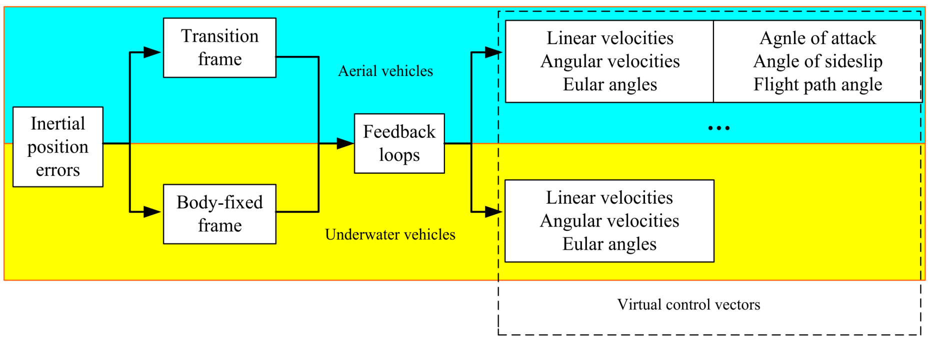


Figure 5. The Lyapunov-based backstepping method for AUVs and UAVs.

For multirotor HAUVs, Neto established a dynamic model of the trans-media process, regardless of the added mass and external disturbances during the water–air transition process [19]. The structure of the dynamic models in air and underwater are similar, since air and water are both fluid. Added mass and floatage are extra-specific in water. Following this, the nonlinear dynamic models in air and underwater are transformed into linear variable parameter models, and the state feedback attitude controllers are designed. Simulation results showed that the proposed control scheme could achieve attitude stability in a preset medium [35]. This is the first attempt at air–water trans-media control. Maia designed switching PID controllers for air and underwater mediums. Euler angles and altitude in air or depth in water were controlled regardless of the horizon position. Underwater fixed-depth experiments were performed using an HAUV in Figure 4a called 'Naviator'. It was equiped with a water pressure sensor which could measure its underwater depth. The depth error reached one meter. Ravell defined the water–air trans-media process as the transition zone. The dynamic model was divided into the flight model, underwater model, and transition zone model. Then, the gain-scheduling control scheme was developed for the trans-media process. It achieved vertical ingress and egress on 'Naviator' but could not track maneuver trajectories [36]. Mercado introduced the unit quaternion to describe the attitude motion to avoid this singular problem and designed the water–air switching cascade PID controller. It could track the underwater maneuver trajectories on

'Naviator' [37]. Added mass, water surface effect and disturbance were not considered, so that the control effect of egress on the process was not considered good. Furthermore, the adaptive sliding-mode controller and the adaptive dynamic-surface controller were developed with the added mass. The parameters' uncertainty and external disturbances were considered [38]. Simulation results showed good tracking ability. However, the controllers were limited, since the Euler angles and the altitude–depth were controlled while the horizonal positions were not considered. So the coutrollers could not track aerial or underwater trajectories.

Morphing HAUVs, especially the variable-sweep wing configuration, were widely adopted. However, there are few researches on the controller design of the multidomain locomotion of the morphing HAUVs. Some tentative works concerned the take-off control after a morphing HAUV left the water. Feedback linearization and sliding-mode control were applied to achieve the take-off control of the variable-sweep HAUV that kept it in a pull-up condition while holding a large AOA [39]. The morphing process, parameter uncertainties, and control-input saturation were further considered with a constrained adaptive backstepping take-off controller [40]. More recently, Chen proposesd a multi-objective trajectory optimization method that was based on the Gauss pseudospectral method [41]. Then, a well-planned dive trajectory could be used for the trans-media maneuver and control. The authors thought that trans-media based on the trajectroy optimization would be the most promising and practical research route.

4. Conclusions

It has been nearly 70 years since the introduction of HAUVs by Ushakov. In the last 10 years, unmanned morphing HAUVs and multirotor HAUVs have been rapidly developed. At present, HAUVs are always designed to be neutrally buoyant. Ideally, such a system could remain fixed underwater indefinitely without utilizing energy, but it is inefficient for flight. The control schemes are limited to the trans-media process and lack of experimental verification. It lacks the overall motion control of air flight, underwater navigation, and the trans-media process. Underwater localization of small-scale HAUVs also appear to be a major challenge, since GPS signals are blocked in water. Additionally, specific application scenarios need to be further studied and clarified to promote the development of HAUVs.

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