Survey of the emerging bio-inspired Unmanned Aerial Underwater Vehicles

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Abstract. Unmanned Aerial-Underwater Vehicles have been envisioned as a new kind of hybrid unmanned system capable of performing equally well in multiple mediums and seamlessly transitioning between them. Currently, bio inspired vehicles are leading the way in the development of such a vehicle, that can fly like an eagle and swim like a fish. This path-breaking amphibious aerial underwater vehicle is sought after because of its wide range of applications in military, commercial and civil environments. From aerial surveillance, deep water exploration to underwater non-destructive testing, this vehicle aims to do it all. However, the development of a fully functional version is hindered by the significantly different properties of air and water, considering the air water transition, different propulsion systems and stability underwater. We evaluate these available architectures that aim to accomplish the goal of creating a flawless multi-medium unmanned vehicle which has its limitations as one of the modes is dominant leaving the other to be at a lesser than expected measure. This paper presents a survey discussing the evolution of these systems by first looking at their parent systems and then evaluating the various existing types of UAUVs by understanding their working mechanisms. The paper aims to provide a comprehensive overview of the work done in the field so far which can provide direction to the further development of such vehicles.

1. Introduction
In this world of growing domination of technology in almost every field, robots have been at the center of this revolution. Many mechanical systems have been automated partially or completely by making robots for specific applications. Drones or unmanned vehicles are a class of robots that have been used in air or in water for a variety of applications from underwater exploration to door step package delivery. The application base for these robots is increasing with every passing day and this expands the scope of its usage. Another approach to evolution of these systems is integrating the aerial and underwater abilities into one to perform tasks with ease across mediums. Mapping and exploration of inhospitable regions where any means of human access is either incapable or extremely dangerous to life, an unmanned hybrid vehicle is needed. It is desirable to launch the unmanned vehicle from the control station or ship to the target position. The interest has further grown as unmanned vehicles have seen a dramatic increase in their use for civil and military applications. This has incentivized the interest in a platform capable of air and underwater operation.

The variety of applications and possible future scope makes it an exciting proposition to look forward to. It is important to understand the systems that this new concept is derived from. It is a bio-inspired design with an aim to emulate the flying ability of a bird and the swimming capabilities of a fish. UAVs are the parent that gives the new technology its flying ability and its underwater operation is derived from UUVs and USVs. This makes UAVs, UUVs and USVs germane to the discussion. Since aerial
underwater vehicles are still a relatively new phenomenon, its novelty demands us to look into the evolution of this idea to understand the system better and help us build a product that is the best technoeconomic solution to the problem. So, the paper first look at aerial remotely operated vehicles and underwater remotely operated vehicles or autonomous vehicles which forms the skeleton of this discussion. The focus then shifts to other multi-media vehicles previously developed. This gives an understanding of what went wrong or what desirable characteristics these machines were able to incorporate. A thorough understanding of the path gives direction to the efforts of the future and by objectively evaluating current systems in conjunction with past and their predecessors can suggest the best way forward for UAUVs.

2. Overview of the types of Unmanned Vehicles

2.1. Unmanned Aerial Vehicles (UAVs)
Unmanned aerial vehicles are a class of aerial vehicles which can be operated remotely without having any onboard presence, with the help of a communication system between the vehicle and the operator. These can be fixed wing or rotary wing UAVs. Both these types have further subdivisions, and the type of UAV used depends on the specific purpose the UAV is designed for. Fixed winged aircrafts have a simple aerodynamic structure, using airflow over their wings to provide lift. Thus, they need to be in constant motion, while rotor wing aircrafts can be stationary mid-air due to generating lift from constant rotary motion of rotor blades. Fixed wing UAVs inherent design promotes gliding without power and thus these UAVs have higher range as compared to rotor wing UAVs. Rotor wing aircrafts have vertical take-off and landing capabilities, and are often seen in the form of quadcopters, which are sought after due to their small size, easy control and high manoeuvrability [1].

Recent years have seen a surge in the evolution of these technologies, with unmanned aerial vehicles being developed for applications ranging from military applications to drone enabled package delivery. Search and rescue operations also have great potential for integration of drones, which can provide better success rates and safety in search and rescue operations [2]. Use of small drones for collection of traffic control data has also been theorized as a field of use, to counter the costs and restrictedness of current methods using human counters and video recording devices [3]. One the most widely seen civil applications of drones is in photography and videography. In all the above applications drones prove to be more efficient and cost effective than the traditional methods, and thus have been proposed to be the new norm instead of many existing technologies.

2.2. Unmanned Surface Vehicles
Unmanned surface vehicles are vessels which operate on the surface of water, and can be remotely operated or autonomous. USVs have been developed from as early as the second world war, although only from the 1990s has this technology seen a surge in development [4]. USVs can be made in many different forms but the mains components remain the same, which include propulsion system, GNC
systems, communication systems, data collection equipment and ground stations. USVs prove to be advantageous as they are able to operate in conditions where human safety would be at risk, and are compact vehicles with low maintenance costs [5]. Small coastline teams can ensure quick deployment of USVs, without establishing any prominent infrastructure [6]. Despite these advantages, the widespread popularity of UAVs is not reciprocated in USVs.

USVs were originally developed for naval applications like surveillance and reconnaissance, but have now moved into the civil domain with applications such as environmental monitoring and assessment. Onboard camera enabled USVs can be used for surveillance in conditions where substantial human risk is involved. Developing applications also include search and rescue, autonomous shipping and offshore surveying in oil and gas industries. Future developments in USVs aim to provide lower operational costs, improved range and autonomy, to push these devices towards mainstream usage [5].

2.3. Unmanned Underwater Vehicles

Underwater vehicles (UUVs), are robots that operate under the surface of water with minimal or no human operator intervention. They include both Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV).

2.3.1 Remotely operated vehicles (ROVs)

These tele-operated vehicles used for installations underwater and various tasks of repairing. These vehicles are majorly used by offshore industries because of characteristics like high safety, reaching great depths, having a longer endurance and their less demand for support equipment. Information is sent to the ROV through a tethered cable or acoustic link by an operator onboard a surface ship.

2.3.2 Autonomous Underwater Vehicles (AUVs)

These vehicles require no constant monitoring or supervision from a human operator. AUVs are not limited in the depths they can dive up to due to the absence of an umbilical cable as in the case of ROV’s. AUVs can be categorised as: a) Safe distance operation from the sea bed, including the use of Sonar for observation of the sea floor, water composition examination, sampling of floating creatures; b) Close proximity inspection of the sea floor and structures made by man, such as hydrothermal activity inspection, creatures on the seafloor and underwater structures; c) Interactions with the sea floor and man-made structures

One of the main difficulties faced by AUVs is the inherent nonlinearity of the underwater vehicle dynamics. Due to many other uncertainties a prediction or calculation of hydrodynamic coefficients need to be performed. Some other challenges faced are limited operational underwater navigation sensors, low visibility during the use of vision sensors and underwater external disturbances.

AUVs operate within a highly unstructured environment which pose difficulties in navigation via information received from satellites. AUV navigation takes place by INS, and acoustic systems, but due to an increase in the endurance of AUVs, their utilization has been more restrictive in terms of
affordability and range. Current involvements include improvement in battery technology, underwater communication, fuel cells, sensor fusion and propulsion systems.

![Figure 3. USV](image)

2.4 Need and Evolution
UAVs, UUVs and UAUVs in their respective fields are able to perform tasks with extremely high levels of precision and are constantly evolving and bettering its previous iterations. This increased interest in unmanned vehicles has led to the rise of various applications never thought of before. Underwater ship hull testing and delivery of relief aid in times of disaster are all possible in today’s world where technology is making human life easier with each passing day. The gradual improvement of these systems is key to further develop and make use of these systems in more testing real world environments.

Another tangent of development is the integration of two or more of these systems to achieve synergistic interaction of these mechanisms to perform multi-media operations. This ability allows the vehicle to transition with a relative degree of ease between different mediums and that opens up new avenues in the applications of drones. By integrating the best of flying abilities and swimming abilities of UAVs and UUVs, a new line of devices is created that are equally able in both air and water. Military grade reconnaissance to recreational photography or exploration are some of the possible applications of this newly emerging technology.

2.5 Unmanned Aerial Underwater Vehicles (UAUVs)
There are biological species like the squid, the flying fish or puffins that are capable of operating in water and air. However, they have a mode of operation they are better at and the other mode is an additional underdeveloped ability. Taking inspiration from this concept, UAUVs are vehicles that are capable of operating in both air and water. They may have a dominant characteristic being more functional in air or water or be equally able in both media. Development of these systems has been tries and various such machines have been successfully implemented. The table below from a survey by Beihang University [11] shows the different types of air water systems that have existed.

| Name          | Institute                     | Morphing structure design | Transition Water-Air | Air-Water |
|---------------|--------------------------------|---------------------------|----------------------|-----------|
| Gull Series   | Warrior (Aero-Marine Limited)  | None                      | Running              | Floating  |
| Flying Fish   | University of Michigan         | None                      | Running              | Floating  |
| System              | Developer                 | Flight Characteristics | Control System |
|---------------------|---------------------------|------------------------|----------------|
| Switchblade         | AeroVironet Inc.          | Catapulting            | Plunge diving  |
| Flying Fish prototype | Beihang University       | Running                | Floating       |
| Gannet              | MIT Lincoln Laboratory    | Hand launched          | Plunge diving  |
| Flying Squid prototype | Imperial College, London | Water jet propulsion    |                |
| Cormorant           | Lockheed Martin Company   | Rocket propelled        | Splashing down |

These systems have had limitations in one of their two core functionalities as one of them becomes a dominant trait and the other is merely an added feature. Systems today emphasize on equally able operations in air and water, along with seamless transition between mediums and the ability to float or glide on water. The goal is to create a system that can swim like a fish and fly like a bird. There are a few mechanisms that have attempted to achieve this and the main systems are discussed in the following section of this article.

3. Types of UAUVs

3.1 Ballast System

A hybrid unmanned aerial-underwater vehicle can use a ballast tank for active buoyancy control and seamless air-water and water-air transition. The depth control system in such a vehicle will consist of the following components: 1) Water-proof hull 2) Water pump 3) Two-way valve 4) Water cylinder 5) Water pump controller. UUVs’ can dive in one of two ways, Static dive or Dynamic dive. 4 concepts are comprised within these two methods: 1) Air compressor-based ballast system 2) Hydraulic pump-based ballast system 3) Piston tank ballast system 4) Direct thrust system

Dynamic diving is achieved by direct thrust system, whereas static diving is accomplished by the first three concepts. The system reviewed in this survey uses a combination of hydraulic pump and piston tank-based ballast system in order to reduce power load on rotors. As compared to dynamic diving, static diving allows depth control of vehicle underwater and 90-degree flip with minimal power consumption.

![Figure 4. Hull of the Ballast system](image)
Figure (4) shows the components of a ballast system as constructed in the Loon Copter. It consists of a hull, a water pump, a two-way valve, a piston and a water cylinder. All the components are mounted in the hull and it also holds the compressed air. The vehicle’s stability is improved as during diving the movable piston holds the water in the water cylinder. The capacity of the water cylinder is 150 ml, out of which, 100 ml is used for diving process and the remaining capacity is used to control the depth of the vehicle. When underwater, the compressed air will attempt to push the water out of the water cylinder, this action is countered by deploying a two-way valve.

When the vehicle is on the water surface, the cylinder and the hull will have air at ambient pressure. As water is pumped into the water cylinder, the transition begins. The air in the hull starts to get pressurised as water is pumped into the cylinder. The process of tilting and submerging occurs simultaneously when the cylinder is filled with water. In a similar manner, the vehicle achieves water-air transition when the water in the cylinder is pumped out. Figure (5) shows a visualisation of the air-water transition.

3.2 AquaMAV
AquaMAV is another unmanned aerial underwater vehicle that is different in concept than its counterparts. It was ideated with the sole application of water sampling in mind and it provides one of the most efficient, safe and cost-effective systems that can achieve collection of water samples and go back to its launch site where the recorded data can be evaluated to then perform necessary action. This is another bio-inspired mechanism that tries to emulate the flying or gliding ability of squids. These animals are known to generate a high impulse gliding leap by discharging a jet of water that gives them enough momentum to fly out of water. The researchers at Imperial College, London took this very mechanism and tried to implement it on a tiny fixed wing aircraft that could perform a similar task.

The AquaMAV works on the principle same as a jet thruster. The thrust in this case is obtained from the expulsion of pressurized gas that imparts high velocities to the vehicle which facilitates it’s launch out of water. 5ml of 57 bar CO2 gas is stored inside a little tank in the vehicle which allows this mechanism of air-water transition.
The robot has a few important components that contribute to the success of the mechanism. The wing is divided into six segments with the leading edge acting as the free end and the root segment hinged to the main body. It is regulated in such a way that when the leading edge is regulated, all segments of the wing follow. This is needed because while entering and exiting or plunging out of water the robot has its wings retracted and opens only when in flight. In this mechanism, the robot dives into water at a steep angle and collects the water samples it needs and then plunges out of water when the plunging mechanism actuated which release the pressurized gas. This provides the robot with the thrust required by the vehicle to fly out of water. Since it jumps out of water at a considerably high speed, it already has the takeoff velocity required for it to fly in the air phase. This unique way of achieving seamless air-water transition is extremely effective as shown in calculations in (citation).

The design is based on basic fluid mechanics by using the unsteady Bernoulli’s equation. The objective function to be maximized in this mechanism is impulse. All calculations are based on creating maximum impulse from minimum space and the properties of gas is decided according to this consideration.

Dual air-water operations always come with their own challenges. The other mechanisms where a quad or octa rotor system is used, is also capable of performing underwater tasks using the same propellers that generate thrust in air but operation in water demands a much lesser rotor speed. However, this would mean that the rotors spin at speeds lesser than their designed range. But these multi rotor systems can be used for multiple missions back to back, while that is something the AquaMAV is not capable of. This robot is more suitable for more frequent applications where it can be used in short intervals for a lesser period of time.

As discussed earlier, the AquaMAV is primarily made for testing of water samples in different civil, military and disaster relief applications. It’s ability to accurately reach points to test is something that the plunging mechanism provides for. The same is very difficult to achieve in multi-rotor systems as the change on rotor speed affects its positioning. An additional advantage of this mechanism is that it is relatively cheaper. A more cost-effective and robust design makes this the most suitable device for this particular application. It can be used by government environmental bodies and researchers to test the health of an ecosystem. This is done periodically and by using this vehicle collecting and testing samples becomes faster. In times of disaster, when locations are rendered inaccessible to personnel, say after a flood or in case of an earthquake, the robot can reach the isolated location with relative ease and bring back essential data like the quality of water or the presence of toxic materials on the water.

The AquaMAV in this way takes an alternative path to solve a particular problem and brings the most optimum solution to the table. Moreover, the AquaMAV is important to understand this evolution of multi-media unmanned vehicles and analyse its future scope. This revolutionary take on doing things
is sure to encourage researchers to look outside the confines of multi-rotor systems to build an unmanned vehicle that can fly and swim with equally able mechanisms.

3.3 Octa-rotor Mechanism
Single or multi rotor vehicles are an alternative to fixed-wing aircrafts. The major advantage offered by single/multi rotor vehicles is their ability to take off and land vertically. Octa-rotor system redefines multi rotor VTOL operations in order to achieve smooth air-water and water-air transition.
As shown in figure (3), each vehicle arm is equipped with dual motors. There is a column gap between the two motors that facilitates the transition.

![Image of Octa-rotor Mechanism](image)

Figure 7. Octa-rotor Mechanism with air-water transition stages

The octa-rotor system is completely reversible, which allows for an air-water as well as water-air transition. Both the propellers on an arm are generating lift as the vehicle approaches the water-air interface. The top propellers are slowed while going through the interface in order to achieve a smooth transition. They accelerate again as soon as they are completely above the surface of water to generate lift. The bottom propellers follow a similar pattern where they slow down as they approach the water-air interface and accelerate again as they exit the water surface to generate lift.

The water-air transition involves complex interaction of the propellers with the surface of water, so in order to avoid a spike in drag, the method of slowing or stopping of propellers is adopted. The transitions demonstrated in figure are performed under two seconds, which realises the seamless transition.
The capability of propellers to generate lift and thrust is fully exploited in this method. Underwater vehicles need to be almost neutrally buoyant and generate thrust at the same time. The propellers are used to generate the required thrust underwater.

4. Applications and Future scope
Civil: Utilisation of drone technology for civil applications has been blooming in recent times. Drones are used in disaster management and relief supply operations. Offshore technology and ecosystem monitoring, including testing of water samples, near water sampling, flora and fauna monitoring can be carried out with the help of drones.
Military: Out of the multiple applications of drones utilised by the military sector, drones can be majorly used as single combat weapons for air or above sea weapon detection, underwater submarine and torpedo detection along with assisting in information acquisition, communication relay.

Development of drone technology and applications of drones in multiple fields is increasing at an unprecedented rate. Future drones can make their way into fields of geoscience, environmental monitoring, agriculture, atmospheric sciences, metrology including atmospheric sciences. The addition of hybrid aerial underwater vehicles to the fleet of unmanned will provide a completely new paradigm to the applications of drone. It gives an additional angle to military reconnaissance and this will remain an area of interest and hence an area of development. Further work is needed in defining specific application-based robots that specialize in tasks that are well suited to this kind of system. In the civil or recreational domain, further development will be focused on making the drone more accessible and easier to control in a way that it appeals to the audience.

5. Conclusion
With every emerging technology, it is important to understand its course of evolution to understand its present and future scope. As this paper surveys aerial underwater vehicles, it glances through its potential parents’ UAVs, UUVs and USVs. In this survey, we have looked at a few relatively new technologies, capable of multi-medium operation, focusing on the transition between the two mediums, namely unmanned aerial underwater vehicles (UAUVs). A brief analysis of bioinspired vehicles suggests that for similar performance in both mediums of air and water, conditions which produce lift and thrust for flight, and conditions which provide near neutral buoyancy and thrust for swimming, overlap. The transition between the 2 mediums is seen to be the biggest challenge in the development of such technology being able to perform both air and underwater missions. The paper discusses two systems which can achieve the desired results, ballast tank with active buoyancy control and a dual propeller system, analysing the advantages and limitations of each system. While both use rigid body dynamics to tilt themselves underwater, the mechanisms deployed for the transition of medium are significantly different. It also explains the AquaMAV, which works on an aquatic jet thruster mechanism. These mechanisms provide the basis for future development by incorporating them in focussed applications that can be catered to. The wide range of possibilities makes this technology an exciting prospect.

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