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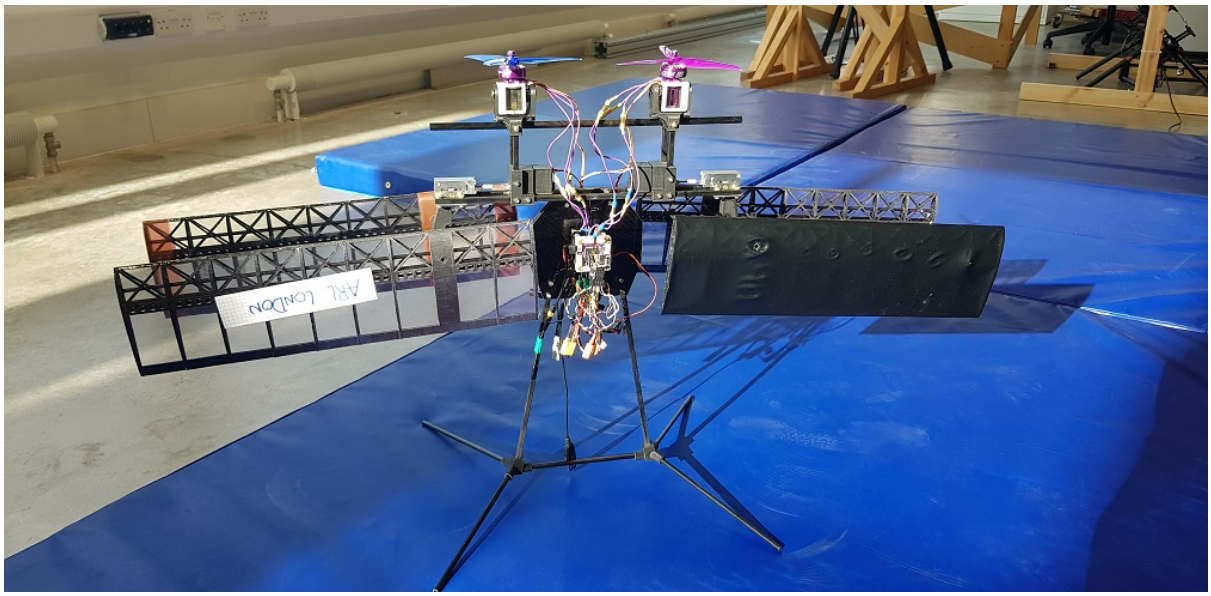
Imperial College of London

Department of Aeronautics

Aerial Robotics Laboratory

Development of a plunge-diving aerial aquatic drone with foldable wings for applications in water analysis

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by DI TRIA Julien

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Submitted in part fulfilment of the requirements for the degree of

Master of Philosophy

June 9, 2024

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Abstract

Currently, water analysis in rivers, lakes, oceans, or dams relies on traditional methods developed by biologists, oceanographers, and microbiologists. These methods involve human operators travelling to the site, collecting samples, storing them safely, and transporting them back to the laboratory for detailed examination. This process is often repetitive, time-consuming, and potentially hazardous.

This thesis proposes using drones to automate and improve the efficiency of water analysis, thereby reducing the workload and exposure to danger for human operators. The research explores the feasibility and challenges of using drones for each step of the water sampling process.

For drones to replace humans in water sampling, they must perform tasks autonomously, quickly, and reliably. Most modern drones can navigate between GPS positions, avoid static obstacles, and land and take off autonomously. However, current drones face significant limitations when it comes to landing and taking off from water. No commercially available drones are designed for these tasks, as their mechanics and electronics are not suited for water environments. Onboard water analysis is possible with specialized sensors, but typically offers limited performance. Although integrating water sampling systems into small drones has shown promise, further development is needed.

The project addresses the challenges of landing and taking off from water, and sampling water with small-scale drones, focusing on the complexity and uniqueness of the required components. It involves mechanical design, electronics solutions, software development, and practical implementation of functional UAVs capable of air-water missions such as water analysis and inspection. The research focuses on a platform: BADAS, for designing a plunge diving platform.

Acknowledgements

I would like to thank all the people who made this project achievable. First of all, I'd like to thank Prof. Mirko Kovac for having me in the Aerial Robotics Laboratory at ICL and making this research feasible. I further wish to thank Andre Farinha, Dr. Sophie Armanini, Dr. Rapahel Zufferey, for their continuous work and experience sharing allowing to progress rapidly in the domain of multi-media drone design, control, and manufacturing. A warm thanks for Assistant Prof. Salua Hamaza for supervising me all through the COVID period and listening to every success and failure during the time alone. Special thanks for Peter, Feng, and Berm for the time spent together in the lab making the drone fly.

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Acronyms

ABS Acrylonitrile Butadiene Styrene. 32, 38, 45

AC Aerodynamic Center. v, 22, 24, 36, 37

AoA Angle of Attack. 36

ARL Aerial Robotics Laboratory. iv, 3, 6, 41

AUV Autonomous Underwater Vehicle. 7

BADAS Bicopter Aerial anD Aquatic System. iii, 23, 37, 38, 40, 42, 48, 49, 51, 52

CAD Computer-Aided Design. 22, 36

CL Lift Coefficient. 36

CoB Centre of Buoyancy. v, 22, 24, 36, 37

CoG Centre of Gravity. v, 22, 24, 36, 37

DoF Degree of Freedom. 25, 52

EPA Environmental Protection Agency. 11, 12

ESC Electronic Speed Controller. 25

FCU Flight Controller Unit. 42

GCS Ground Control Station. 6, 8, 9

NBDM Non-BackDrivable Mechanism. iv, 39–41, 52

PC PolyCarbonate. 45

PEEK PolyEtherEtherKetone. 45

PET PolyEthylene Terephthalate. 45

PETG Glycol modified version of PET. 45

PLA Polylactic Acid. 38, 45

PP PolyPropylene. 45

PVC PolyVinyl Chloride. 45

PWM Pulse-Width Modulation. 42, 44

QGC QGroundControl. 8, 9, 14

ROV Remote Operated Vehicle. 5, 6

RPUF Rigid polyurethane foam. 32

Tg Glass Transition temperature. 45

TTC Time-To-Contact. 30

UAAV Unmanned Aerial-Aquatic Vehicle. iii, 1, 7

UAV Unmanned Aerial Vehicle. 1, 5–7, 17, 27, 29

VTOL Vertical Take-Off and Landing. iii, iv, 27

1 Motivations

1.1 Thesis statement

The goal of this research is to design a drone capable of achieving water analysis underwater (5m depth) with a long-range capability (less than 10 kilometers), and the capability of takeoff and landing in narrow areas (a few square meters). Those 3 requirements are not challenging when taken individually, but when added together, the constraints that they impose are quite restraining, and compose the main challenge to overcome for this research.

The scope of the work done during this thesis has been reduced due to the COVID situation in 2020, delaying the research in lab. The complete testing of the drone was left out of the scope, focusing on the design and manufacturing.

1.2 Multi modal Unmanned Aerial-Aquatic Vehicles

Given their flight capability, Unmanned Aerial Vehicles (UAVs) are allowed to cover longer distance quickly, avoiding most land obstacles faced by mobile robots (terrain, traffic, dynamic obstacles). They encounter different obstacles, like landing without breaking, reduced autonomy due to weight, weather changes, but the space that they could reach and the applications have been greatly extended.

One particular application is the interaction with water, mainly in the domain of ecology and biology to carry out measurements, water sampling, marine investigation, autonomous monitoring of fragile environment or industrial maintenance. In this optic, Unmanned Aerial-Aquatic Vehicles have been researched as they can move faster than water-robots, as well as move across different bodies of water.

The scientific community and its literature on UAAVs is getting extensive [4], covering flying vehicles of a very various size, from wingspan in the micro-scale to multi-meter scale. Many different categories of drones have also been classified, such as jet-thruster, fixed-wing, and more recently ornithopters and rotorcrafts.

Even if a lot of research as been undertaken in the last decade on these robots [5, 6], "UAAVs remain challenging to develop, and fully functioning autonomous and robust prototypes are still scarce" [7]. Indeed, the additional locomotion capability is coming with an important cost, heavier, mechanically and electronically more complex, and more prone to failure. The difference of media and their physical characteristics (density, viscosity) which impact the scale, direction and application points of the forces that the platform has to sustain, makes it challenging to design a robot that is efficient in multi-media locomotion.

1.3 Water analysis using drones

Water analysis is the process to gather water samples and analyse them in order to determine the state of the water (bacteria level, chemical components, micro-organism). The use of the water can then be recommended or discouraged based on its purpose. This process is an important part of the global health of people and animals around the world, as we all use water in our every day life, may it be for drinking, cleaning ourselves, washing hands, cloth, or feeding plants. It's also the main living medium of fishes and sea food, which impact our food chain. Making sure that the water we use is proper depends on regular sampling and analysis to detect as soon as possible any harmful characteristic of the water.

Water sampling is done according to some well defined procedure, under the surveillance (rename) of the World Health Organization [8]. The location, frequency, storage and transport of the sample are the main points of this procedure before reaching a laboratory for analysis. The storage is done without much interaction of the human, but on topic of the location, frequency and transport, using drones instead of relying of humans could improve the efficiency. Location

of water sampling, such as mountain lakes or rivers, can be remote, far and hard to reach, even hazardous sometimes for the operators (for example a creek lake in old mine [9]). The frequency needed for water sampling depends of course of how likely the water quality is expected to change, and then of the ability of doing sampling at higher frequency (limited staff, multiple locations to go to). The transport of those sample is made to carry multiple samples with a total mass that can be carried by humans, either by car or other means of transport.

Drones can impact on those 3 steps by removing the human factor of the process. Flying a drone from the laboratory to the sampling location is safer and can be done in a shorter amount of time, therefore the sampling frequency can increase. The transport of samples by the drone however reduces the capacity and quantity, as small drones can't carry payloads as heavy as humans can (see Figure 11).

1.4 Specific drone platform

Drones can be quite varied, in size, endurance, flight capability, payload capability. They can range from very tiny flapping wings drones [10] of a few grams, to very heavy fixed-wing drones (military drones). The flight capabilities (long-range, hovering, acrobatic maneuvers) highly depend on the drone platform (helicopter, quadcopter, fixed-wings, flapping-wings). These drones are designed to be very efficient for their mission characteristics, and therefore new platforms are created for new application.

Water sampling and water analysis missions require a close water interaction of different types: landing and taking-off on and from water, hovering close to water, diving through the surface, in addition to the water sampling process, like water collection and water filtering. Those interactions are not ready-made for most current drones as there was no need for close-water interaction.

Some drone for water and underwater operation already exist (see Section 2.1.2). They are specifically made for diving in depth, recording video, or manipulating objects. They are capable of doing a very specific mission, but are not suited for water sampling.

New platforms are needed to fulfill these requirements, very specific for each mission. This is why new drones were developed for water analysis. However, creating a new platform for each mission is highly time consuming and resource demanding. The research of this thesis is also focusing on finding common requirements and common methods to reduce the specificity of each platform, looking to have a more general drone or framework that can do multiple tasks.

1.5 Need for a global guide to multi-modal robots

At the time of writing this research, not many drones are capable of doing multi-modal navigation, including multi-media locomotion and transition. Having proper air-water interaction, and good locomotion capabilities in both, medium is not common in the scientific community, for a few of reasons:

- The need for multi-media drones in industry is still sparse and isolated, and can usually be accommodated by single medium drones (fully air, fully water/underwater, or fully ground vehicles).
- Multi-media vehicles need deep knowledge in both individual media in order to merge the capabilities into a single vehicle.
- The incompatibilities between the physical laws in the different media are often underestimated. Indeed, some forces (lift or friction for example) apply at different magnitude in different medium due to the density of the fluid being 10^3 more in water than in the air, which is then hard to integrate into a single platform.

- The autopilot software (flight controller, dive controller, underwater controller) are not ready to be integrated into each other, specially not the transition from one to the other. This is mainly due to the fact that they have been developed without regard for other media because the need never really arose.

An important work would be therefore to create a uniform standard for the different media platforms, including software controllers allowing easier multi-media transition development, summary of physical laws impacting each medium, and a deep knowledge of different domain in multi-media interactions. This framework would simplify the future development of multi-media platforms by providing to researchers the means of easy development of new features without the need to rebuild everything.

1.6 The challenges

Doing water sampling or water analysis with drones can be done in different ways. The common tasks are the following:

- Navigate to the sampling location
- Take one or multiple samples
- Analyse the sample, on the spot or back in the lab
- Return to the safe location

For each of these tasks, multiple challenges arise depending on the specific mission requirements. For example, if the sampling location is far from the starting point, this imposes a constraint on the battery life of a drone, or its shape (quadcopter versus fixed-wing). If more than one sample is required, the sampling system needs to be made such that no cross contamination can happen. Based on the type of analysis to be done, the quantity of water needed is different and imposes a payload requirement on the drone.

1.7 Research objectives

The thesis research focuses mainly on the research and development of a multi-modal platform for aerial-aquatic locomotion, exploring and finding solution for the design and manufacturing of the robot. The research on the water analysis was done in collaboration with another project and is not entirely shown in this thesis. The requirements are however kept in mind when exploring the world of possible solutions for a multi-modal robot.

The main research objective is therefore the design, analysis and manufacturing of a feasible prototype for an aerial-aquatic robot, with capabilities beyond currently existing solutions: flying, underwater navigation, dynamic diving and take-off from the water and vertical take-off and landing on the ground all integrated in one single platform.

This thesis search to answer the question : "Can a drone exist that could have the capability to do seamless transition between the air and water media while having proper navigation abilities in both those media ?" The work contributions are the exploration and research of existing drones and solutions, design a prototype for such a drone if feasible and manufacturing and building the prototype.

Based on previous experiments and work done in the Aerial Robotics Laboratory, by previous Bachelor and PhD students (as shown in Section 2), the research tries to expend the field of application of a drone that was built in the lab by using knowledge of aerial-aquatic drones that has been the field of the laboratory since 2014. The new requirement is the addition of the capability to transport a utility payload, such as a water sampling device, which was not taken into account in all the previous versions of this already multi-modal drone.

1.8 Statement of Originality

The work presented in this thesis is based on the research done by the author during his time at the Department of Aeronautics at Imperial College London. It is the author own work, and the work of other authors included in this thesis is referenced and cited accordingly. No part of this work was used or submitted to another place to obtain a degree.

Julien Di Tria

2 State of the Art

In this section, we'll do an overview of existing technologies that are already available closely related to our project.

2.1 Drones

Many drones exist in the community [5, 11, 12, 13, 14], with different shape, weight, application and flight range. They can be classified according to many criteria, but here we go over the main categories of drones based on their medium of operation.

2.1.1 Flying drones

Most common unmanned vehicle are aerial drones. The term 'drone' usually refers to Unmanned Aerial Vehicle (UAV). These UAVs are capable of takeoff and landing on the ground, sometimes with the help of specially made launchers as seen in Figure 1, and capable of flying in the air. Many different categories of drones have also been classified, such as jet-thruster, fixed-wing, and more recently ornithopter and rotorcraft.

The main sub-category in UAVs is their capability to naturally hover (quadcopter Figure 2(a)), helicopter) or not (fixed-wing, plane (Figure 2(b))). This comes with the other properties of long-range and long-duration flights, which fixed-wing drones are better at, as they use less power to stay in the air thanks to their wings. They only need a fraction of the power to propel themselves to a given speed to generate lift, while quadcopter use most of their power to counteract gravity on hovering.

The ornithopter or flapping-wings vehicle (Figure 2(c)) appears in between those 2 categories. Bio-inspired drones can transition between fixed-wing and hovering depending on their configuration, granting a better maneuverability than the common airplanes and better flight duration than quadcopters. They are however generally more complex mechanically speaking.

The last category of flying drones is the "lighter-than-air" drone, such as hot air balloons or helium balloons, also called blimp (Figure 2(d)). They have a very long endurance as they don't need any power to stay in the air, but they can't move very fast due to their big volume and mass, inducing a lot of inertia, compared to the lightweight propeller they can have to control themselves.

Their properties are summarized in the table below.

2.1.2 Water drones

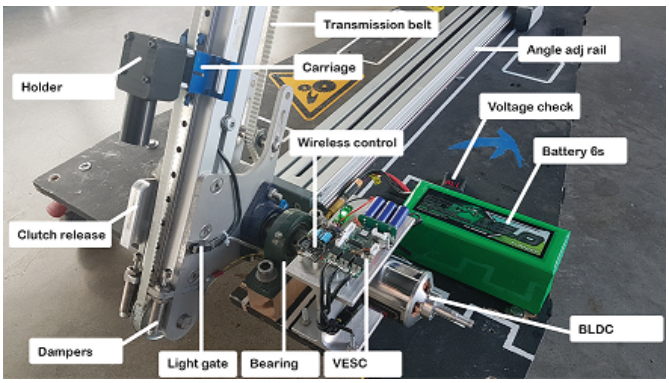
Some unmanned vehicles are designed specifically for water locomotion. They are capable of navigating in water, either at the surface (boats (Figure 4(c))) or underwater (submarines (Fire 4(a) and 4(d)), fish-like (Figure 4(b))). Those underwater drones are commonly called Remote Operated Vehicles (ROVs).

Water surface vehicles can be propelled by different means: using a propeller underwater that generates trust, or using sails that gather the power of the wind to move the boat around.

Underwater vehicles are usually rigid, mostly using propellers to move forward and use buoyancy control systems to control their depths. The buoyancy is the force that a fluid exerts on the immersed drone, counteracting gravity, such that regulating this buoyancy force allows for a depth control. The buoyancy control system can be of different sort, both modifying the total density of the drone: bladder or ballast. Bladder systems change the physical volume of the drone by inflating/deflating an elastic bladder with a gas or another fluid less dense than water. System using ballast change the weight of the vehicle by filling some fixed-size tanks with water taken from the environment. Trimming can be done with similar secondary systems [20].



(a) Aerial Robotics Laboratory (ARL) drone launcher



(b) ARL drone launcher electronics



(c) Professional catapult launcher for a UAV plane [15]

Figure 1: Drone launchers found in commercial application and developed in the ARL at Imperial College London.

Most ROVs tend to be neutrally or slightly buoyant to not sink in case of power loss, which makes them having a average density similar to water (1g/mm3 or 1000kg/m3). The depth control system adjusts around this neutral buoyancy, and can trim the system for neutral buoyancy before applying full control.

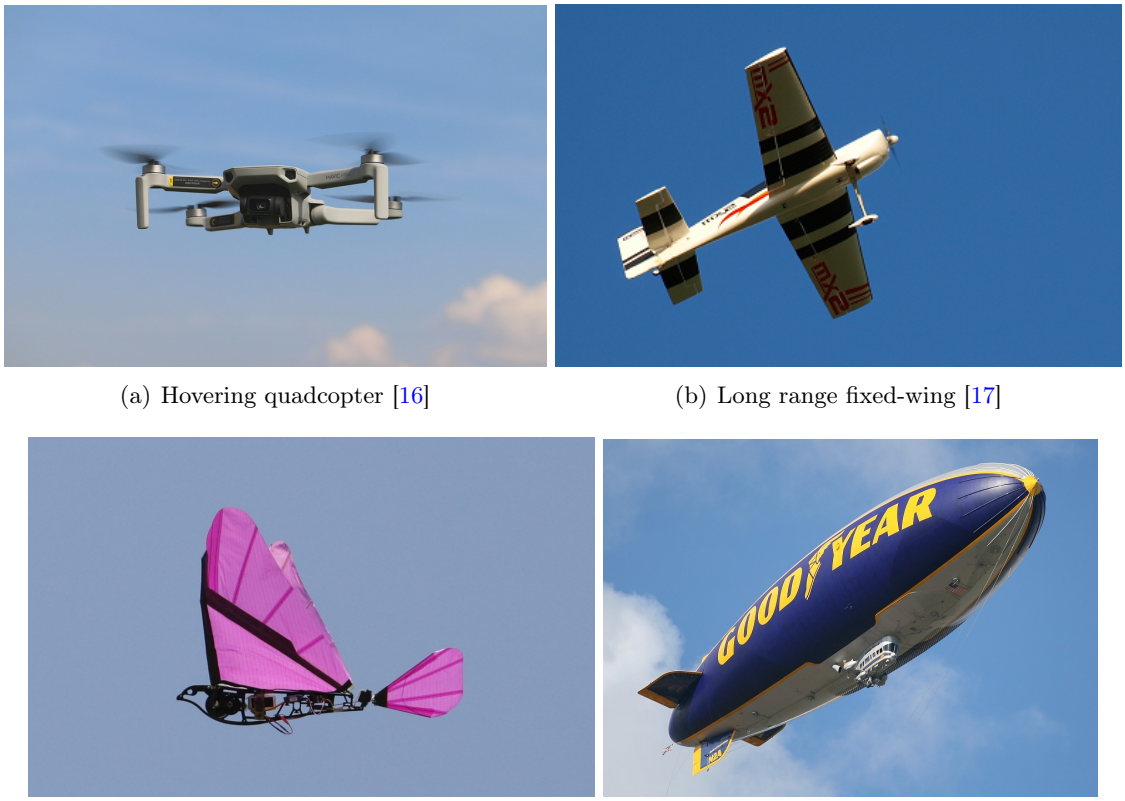
One important characteristic of the ROVs is that most of them are tethered drones. A long electric cable is used to transmit data to and from the GCS, as most radio wavelength (400MHz to 5GHz) don't propagate far in water. This impose a range limitation on a drone area of operation, restricted by the length of this tether.

2.1.3 Multi-modal drones

Multi-modal drones are drone that can operate in different media. They can be ground-aquatic [25, 26], ground-aerial [27], or aerial-aquatic [4, 28, 29, 30, 31].

A last category could be done with ground, aquatic and aerial capabilities, but to the author's knowledge, none have been rigorously presented in the scientific community.

We are going to focus first on ground-aquatic and aerial-aquatic, as ground-aerial don't interact with water.



(a) Hovering quadcopter [16]

(b) Long range fixed-wing [17]

(c) Flapping wing [18]

(d) Blimp [19]

Figure 2: Examples of flying drones

2.1.3.1 Ground-Aquatic vehicles

This category includes drone like airboats (air propeller and gliding on the ground and water surface), amphibian cars, snake-like robot (Figure 6(a)), Cuttlefish shaped (Figure 6(b) [33]), or crawler type (Figure 6(c)). They have different speed characteristic in each medium (table summarizing) but mainly do water surface locomotion. Some cars were turned into submarine (Figure 6(d)) but they are still very futuristic.

Pliant Energy System [2] developed the cuttlefish inspired robots, and showed its multi-modal capabilities in this graph (Figure 7).

2.1.3.2 Aerial-Aquatic vehicles

Also called Unmanned Aerial-Aquatic Vehicles (UAAVs), those drones are very variate. They are vehicles mixed from both UAVs and Autonomous Underwater Vehicles (AUVs), having capabilities from their both parents, moving through air and water, on which the literature is getting extensive [4].

They combine more locomotion type to allows to fly and do surface or underwater locomotion, using different technologies, fixed-wings or rotorcraft are being developed and tested more rigorously to find proper solutions [37, 31, 38, 39].

2.1.3.3 Drone selected for the project

For this project, the goal is to get a drone that can be used to do air-water transition in a small space, while having long range capabilities. From the list of existing drones, none exists that satisfies all of the requirements and constraints defined. Based on this table of criteria, we can

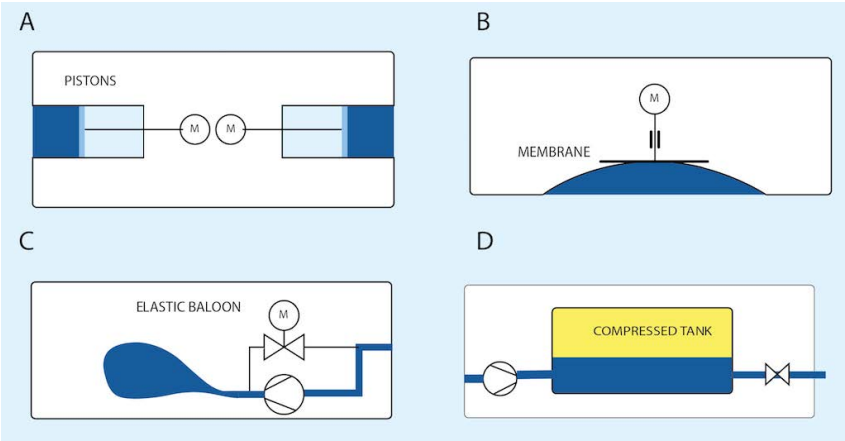


Figure 3: Buoyancy control system [1]

select a group of drone to improve upon while the selection is not definitive at this point. The chosen one is AquaMAV [4].

Through the literature review of multi-modal drones, one can see that the integration of aerial and aquatic mechanism into a single robot is not obvious. Choices of performance or utility will lead to a different drone each time, as there are many ways of combining aerial and aquatic locomotion systems together.

2.2 Controllers

To control the drone while navigating, either in flight, underwater or water surface, autopilots and flight controllers are used. They are needed to autonomously stabilize the robot while giving the control command of the degree of freedom directly to the operator. They transform the operator inputs into motor speed and torque output based on the state of the robot. Using controllers framework allows to have a fast working prototype as developing a new controller from the beginning is very tedious and very iterative.

As the robot we are trying to design and build has to navigate in the air and in the water, the controllers which can be used need to be flight controllers and underwater controllers, the first one being quite common nowadays for quadcopter hobbyist, the second one less known.

2.2.1 Open Source Flight Controllers

Remarque: In the drone community, the term "flight controller" is used both for the physical device as well as for the software program in the physical device, as the physical device is usually programmed with a specific software. Here, only the software of the flight controller is compared, as the hardware can be changed independently.

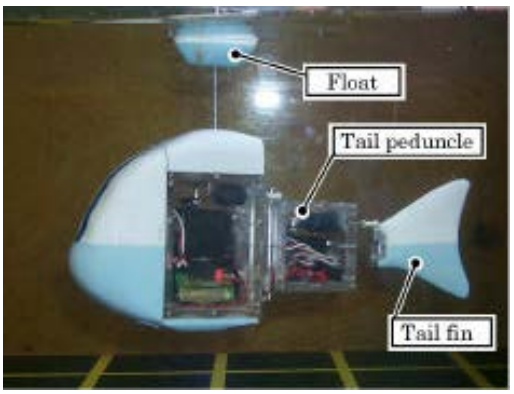
2.2.1.1 PX4

One of the most common autopilots, PX4[40], is an autopilot from 2012, developed initially by laboratories at ETH Zurich, supporting a large variety of airframes, including copters and multicopters (the general category of quadcopter with more than 4 propellers), airships and balloons, airplanes, Vertical Take-Off and Landing (VTOL) drones, rovers and submarines (still experimental at the time of writing).

The software comes with QGroundControl (QGC), a Ground Control Station (GCS) which is used to communicate with the flight controller via WiFi or telemetry modules, allowing to track the state of the drone during a mission. Missions can be generated directly in QGC, and



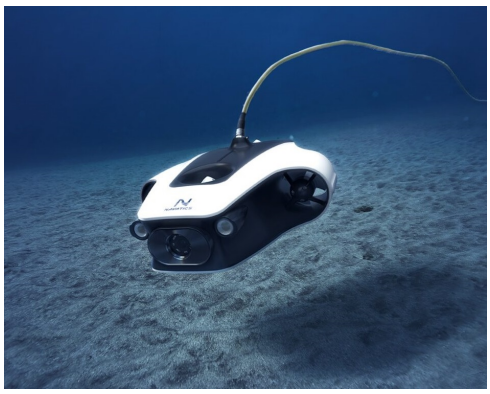
(a) ROV Beluga Planys Technologies [21]



(b) Fish Like robot [22]



(c) Remote Controlled Boat [23]



(d) Navatics MITO Underwater Drone [24]

Figure 4: Examples of water and underwater drones

analysis of the mission can be done live or by downloading the log files afterwards. QGC allows to do on-the-fly re-configuration of the flight parameters of drones using MAVlink, "a lightweight messaging protocol to communicate with drones" [41].

2.2.1.2 ArduPilot

The ArduPilot [42] software suite is an autopilot, developed by hobbyists starting from 2009, to control their aircrafts. It supports multicopters, airplanes, rover and submarines, as done by PX4.

The suite includes two GCS, Mission Planner and APM Planner 2, the first one being originally developed for ArduPilot, the second one being an offspring and combination of the QGroundControl of PX4 and Mission Planner. Both offer missions configuration and drone parameter configuration using MAVlink.

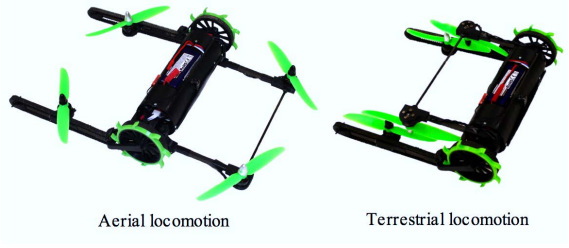
2.2.1.3 Betaflight

Betaflight [43, 44] and its configurator is an autopilot focusing on performance and latest feature additions to its firmware. It is based on Cleanflight [45], itself based on Baseflight [46] from MultiWii RC [47], which was originally developed to run on the Nunchuck of the Nintendo Wii console, using its embedded accelerometers and gyroscopes.

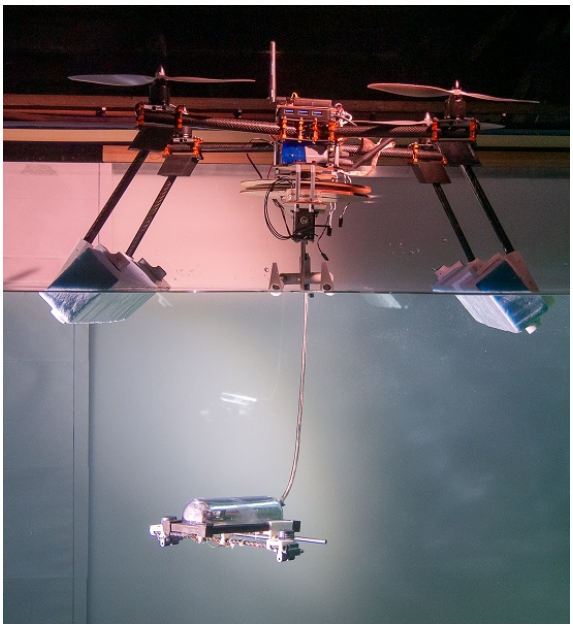
The Betaflight controller is lightweight and has features developed and tested earlier than PX4 and Ardupilot, making it a good choice for testing new features needed for developing a new platform.



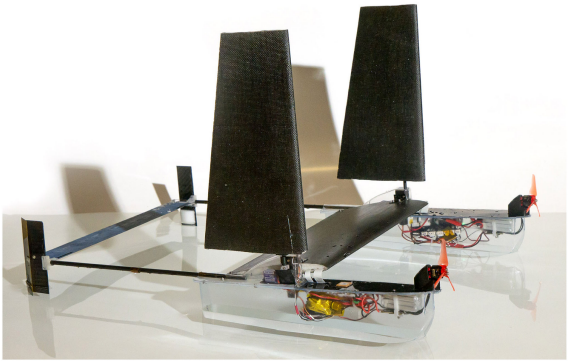
(a) Salamandra robotica II [32]



(b) Multi-modal hovering and terrestrial robot [27]



(c) MEDUSA system in action [29]



(d) SailMAV side view [28]

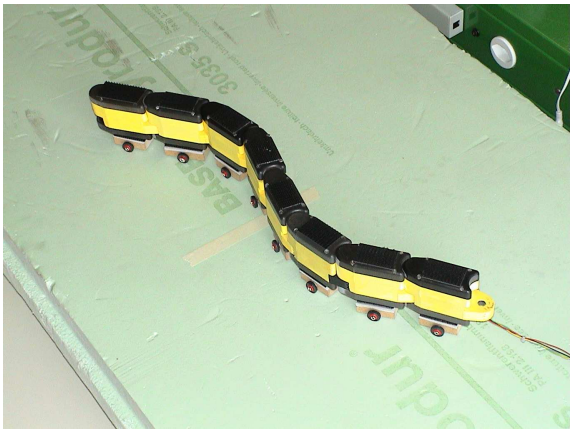
Figure 5: Examples of multi-modal drones

2.2.2 Underwater controller

Specific controller for water and underwater navigation also exists. In opposition with generic flight contorller, they are developed solely for water and underwater navigation, and are usually specific to the platform. For example, Underwater SPECTRE [48] was developed specifically for autonomous underwater vehicles. It can control a variety of underwater vehicles, manned or unmanned, remotely connected with tethered link or intermittent communication, or fully autonomous. It provides a range a capabilities for heading, tracking, dynamic positioning, serial communication or acoustic communication (mainly used in underwater medium), joystick and remote control operation. However, most specific controllers are not open source and would require to buy the software to see the entire capabilities of extensions or integration for a custom platform flying and navigating underwater.

2.2.3 Chosen controller

Based on the research objectives, one critical aspect of the controller is to be open source and to have features already available for flying a custom made airframe, with capabilities for



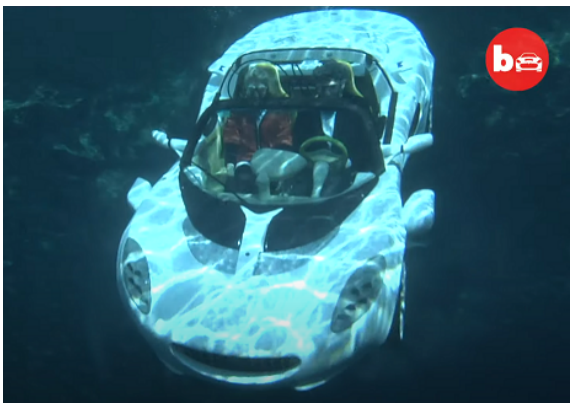
(a) AmphiBotI [34]



(b) An amphibious robot propelled by undulating fins [33]



(c) Amphibious Robot CCTV Inspection Crawler [35]



(d) "sQuba, the world's first and only real submersible car capable of driving seamlessly from land to underwater" [36]

Figure 6: Examples of ground-aquatic drones

underwater navigation as well.

While Betaflight is usually implementing new features as soon as they are available, on the contrary to PX4 and ArduPilot who wait longer to release a new feature, it has been found harder to support custom made airframe and transition between different flight configuration is not supported. Similarly for PX4, less support was available for some transition between flight configuration, while being supported by ArduPilot.

The ArduPilot suite was therefore chosen to allow maximal design choice freedom, as this new platform will be on edges of what current controllers can provide.

2.3 Water analysis

Water analysis is a very broad topic that has been studied in depth by the biology, environment and chemical departments. Here, we provide a summary of 6 topics that can be linked with drone application, and what analyse is done in each. More detailed can be found in King Lim Keith Lee Thesis [49].

1. Drinking water monitoring : This is the most established and applied application of water sampling as it's directly linked with the public health level. The frameworks for measuring water and ensuring that the standards set by the different continental Environmental

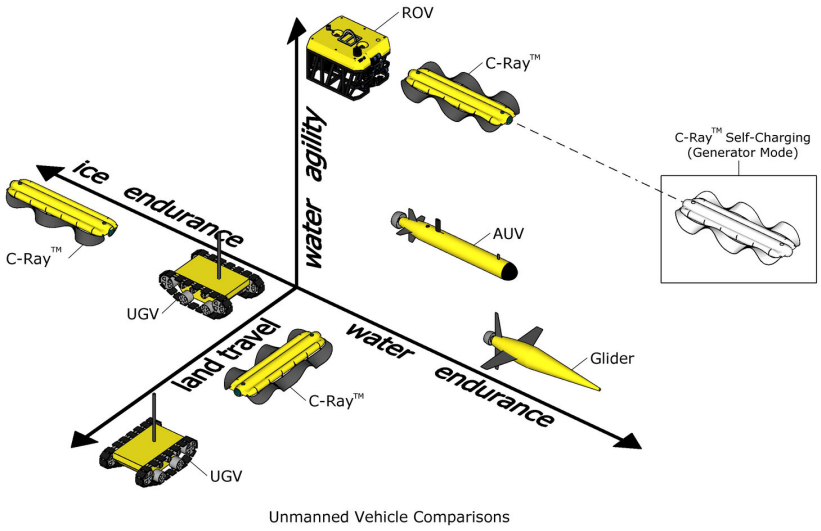


Figure 7: Cuttlefish inspired C-Ray™ [2]

Protection Agency (EPA) are respected is well setup and regularly inspected [50, 51, 8].

2. Wastewater monitoring : Wastewater management is done to control and regulate the wastewater, to make sure treatment is applied correctly until the water is cleaned out. Though it is usually seen as a burden, wastewater treatment allows the water to be recycled, reused, and re-injected into the clean water cycle. Sampling is usually done in multiple points of the treatment, at the influent and effluent location, as well as at the resting location, where the water is separated and cleaned by decantation [52].

3. Ecological Monitoring : Water is also playing a major role in the environment, evolution of each and every ecosystems. Lake, river, ponds and other stream and water body are sampled to monitor their evolution and to detect pollution.

4. Volcanogenic lake analysis : This monitoring and analysis provide insight on volcanic activities, as gases are released with higher concentration before eruption, changing the water composition. The color of the water changing with its composition, a drone survey with camera would allow to not send people in dangerous area and quickly evaluated the volcanic activities [53].

5. Urban flooding monitoring : Urban floods impact more than we allow ourselves to think the quality of the water after these events. The important quantity of water moving out of its usual path makes it transport contaminant that are let on the site of the flood. However flooding monitoring is limited due to the importance of helping humans survive flooding taking priority, difficulties arising even more in less developed countries [54, 55, 56].

6. Oil spill monitoring : Monitoring of oil spill is a big challenge in the current times, as oil is being carried out in large quantities around the globe. As single spill can have major impact on the wildlife, as oil floats on water, dispersing rapidly and covering a huge region very fast. Recovering the oil spilled requires a huge effort that is usually not done, expect when the spill happens in a small confined water bodies [57, 58].

2.4 Water sampling technologies

Water sampling is the first step towards water analysis. It has to be done carefully to avoid contamination of the sample, and in a location that is chosen to represent correctly the state of



(a) PX4 capabilities summarized [40]

(b) Ardupilot capabilities summarized [42]

Figure 8: Flight controller capabilities

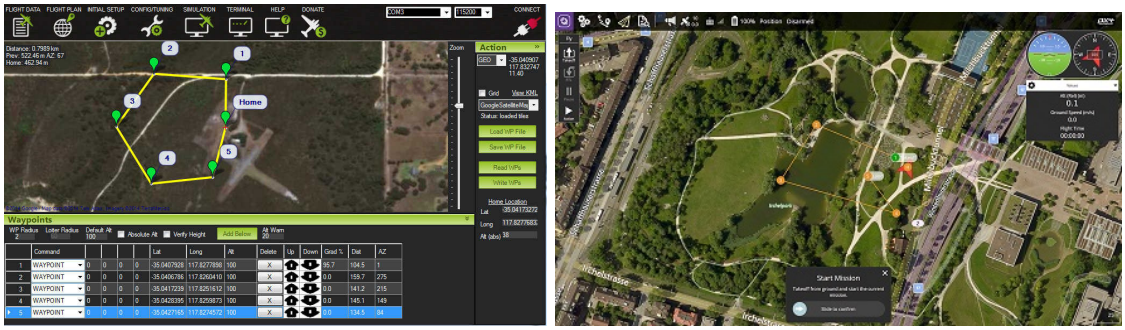
the body of water. If the body of water is big, spatial distribution of the sampling needs to be done and multiple samples taken. Similarly if the constituents of the body of water are expected to change in time, a temporal distribution, usually characterised by a frequency of sampling, is chosen to capture those variation as well as possible.

Based on the type of analysis which is planned for the water, depending on the use of water, the sampling size is also adjusted. It can range from some millilitres to a litre depending on the application [59].

2.4.1 Fixed water sampling

For a lot of cases, the water can be monitored almost constantly using a fixed water sampling methodology. The idea is to have a fixed sampling and analysis station on the water body, which can continuously or regularly take a sample and analyse it.

This can be done for drinking water monitoring for example, where the water follows a fixed path from the source to the tap, or for wastewater monitoring where a continuous control is needed. Both those systems are constructed by humans so having a local station to analyse the



(a) APM home screen [42]

(b) QGC home screen [40]

Figure 9: APM and GQC home screen

water does make sense.

There are ecological benefits of the higher frequency offered by the fixed water sampling methods, but it also needs to not disturb the environment that needs to be analysed, which is not always possible. Indeed, the station for water analysis usually require a fair amount of laboratory equipment which take space and would highly disturb the environment. The need of higher sampling frequency is however still needed.

2.4.2 Scarce and rapid water sampling

For a lot of other applications, having a fixed station is not possible, and would not make sense. In case of an urban flooding, or oil spill, the location, quantity, duration and time of these event make it impossible to have water sampler station that could be setup efficiently.

In those cases, the need for a quickly deployable system to do water sampling is needed. In general, human operator will go on site and do manual sampling to gather some water, then bring it back to a laboratory for analysis.

A common way to do water sampling is simply to fill a clean container with the water up to the required volume by putting it in the water, then close it and store it to protect the sample from degradation, which can incur with sun exposition, change of temperature, mixing with other components, or sometime even shaking. To achieve this sampling, operators might need to take a boat from the shore to the sampling location, travelling a longer distance and at lower speed than by car, specially since it takes quite some time to park and transfer material from the car to the boat.

To sample at a certain depth, bathometers, Kemmerer sample bottles, or Van Dorn samplers can be used. A bathometer consists of a stainless cage in which the container is stored, closed until reaching the desired depth. A single cork can be open and closed remotely to allow water to fill the container. Kemmerer bottle are opened on both side in order to allow water to flow through them while going at certain depth, allowing water from any depth to be collected. Similarly with Van Dorn sampler, the main difference being that the flow is not disturbed while going through the sampler due to it's mechanical configuration. This is an important feature to study layers of water as they do not disturb the water while going at different depth [60].

These methods are used to gather up to a liter of water. However, liters of water are not easy to transport by drone, as the payload becomes to heavy. We are fixing here a limit of 500g of payload for the drone, which is reasonable for a drone of a small size. Following the new European Drone Regulation, "the 'open' category section is the main reference for the majority of leisure drone activities and low-risk commercial activities" [3], which is the classification for our drone project. We therefore wish to stay below the total 2kg limit to stay in the A2 category (see Figure 11).

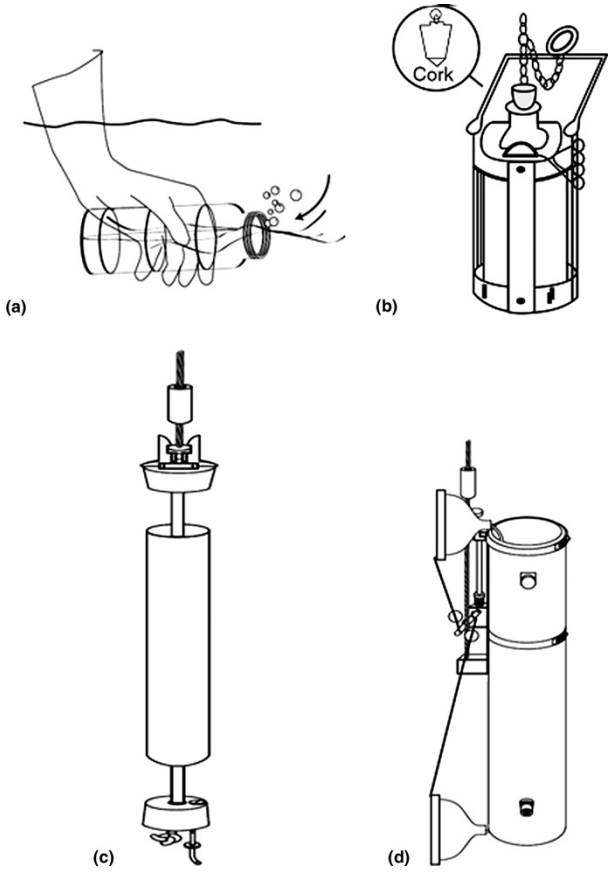


Figure 10: Nonisokinetic samplers used for surface waters. (a) open-mouth sampler, (b) weighted bottle sampler, (c) Kemmerer bottle, and (d) Van Dorn sampler. Reproduced from [60]

Another methods is used by ecologists to achieve water sampling, necessitating only a little amount of water to bring back to the lab: on-site filtering. The method consists of filtering the water by hand through membrane in order to gather only the residue back on the filter to analyse back to the laboratory. This method has the benefit of having very little water to transport, but necessitate some work on site to filtrate the water. This is made when filtering can be done easily on site, as it would have been done in the lab anyway. Figure 12 shows an example of syringes that are used in combination with the filters (Glass microfiber GF/F for example). The vacuum station is used to automatically pump the water through the membrane if the analyse is done in a laboratory.

2.4.3 Drone solution for water sampling

Ever since drones were invented, they have been used for variate tasks: goods delivery, tracking and navigation, military and law enforcement, photography and video, surveillance, as depicted in Figure 13. More recently, their topic of monitoring is being extended to aquatic monitoring, like deep exploration, filming to track fishes, water sampling or even direct underwater interaction with fishes.

Water sampling with drones has been done in mainly two ways:

- Carry a recipient hanging below the drone, which gets immersed in the water when drone lower its altitude while hovering over the water body. The water then fills the bottle or the recipient, which then gets closed by a simple mechanism, and the drone get to a higher altitude to fly back to shore.
- The water is actively pumped from the water-body, and stored in smaller container on the

UAS	Operation		Drone operator/pilot		
Max weight	Subcategory	Operational restrictions	Drone operator registration	Remote pilot competence	Remote pilot minimum age
< 250 g	A1 (can also fly in subcategory A3)	— No flight expected over uninvolved people (if it happens, overflight should be minimised) — No flight over assemblies of people	No, unless camera / sensor on board **and** the drone is not a toy	— No training required	No minimum age
< 500 g			Yes	— Read carefully the user manual — Complete the training and pass the exam defined by your national competent authority or have a 'Proof of completion for online training' for A1/A3 'open' subcategory	16*
< 2 kg	A2 (can also fly in subcategory A3)	— No flying over uninvolved people — Keep a horizontal distance of 50 m from uninvolved people	Yes	— Read carefully the user manual — Complete the training and pass the exam defined by your national competent authority or have a 'Remote pilot certificate of competency' for A2 'open' subcategory	16*
< 25 kg	A3	— Do not fly near or over people — Fly at least 150 m away from residential, commercial or industrial areas	Yes	— Read carefully the user manual — Complete the training and pass the exam defined by your national competent authority or have a 'Proof of completion for online training' for A1/A3 'open' subcategory	16*

Figure 11: Open Category - Civil Drones summary [3]



Figure 12: Solid-phase extraction cartridges and disks, and SPE station vacuum manifold for automated sample processing [60]

drone, closer to its structure. Doing so, it becomes feasible for a system to have multiple samples on board. Another advantage is that there is no need for a recipient hanging below the drone on a long wire that could collide with obstacles along the way. There is still the need of a tube to pump the water, but it can be shorter.

Many systems have been developed with different capacity, payload, flight time and physio-chemical variables monitored [61]. Figure 14 shows some drones and their working principle. [53] used a water sampling bottle attached below the drone by long rope.

2.5 Clarification of the thesis

The requirements of this project can now be better clarified. Indeed the topic was left quite broad from a research point of view until after the state of the art was done.

The topic is the design of a novel robotic platform capable of flying long range, entering the water in a small area, navigating underwater, gathering a water sample, taking-off from the water again, and bringing back the sample to the lab, focusing mainly on the platform itself. The second important part of the project, namely the water-sampling, was supposed to be done

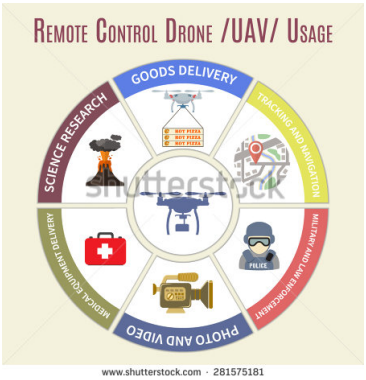
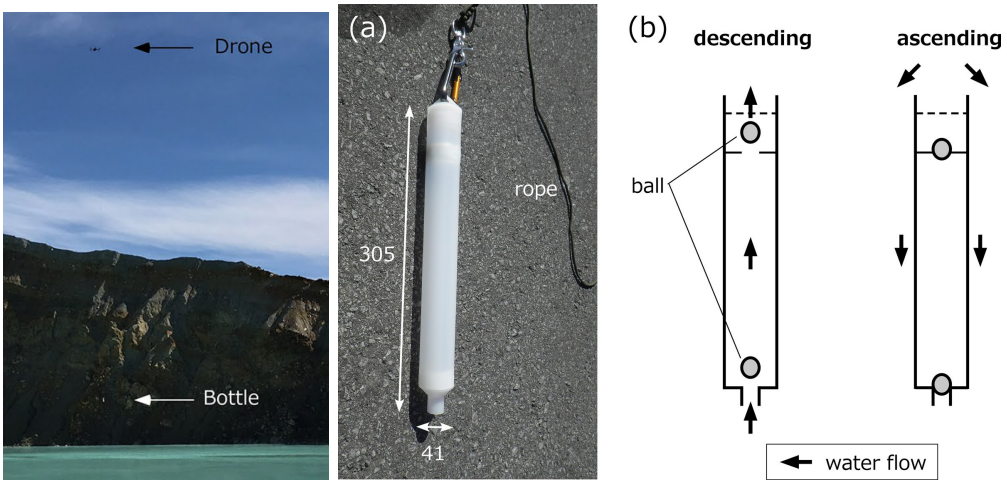
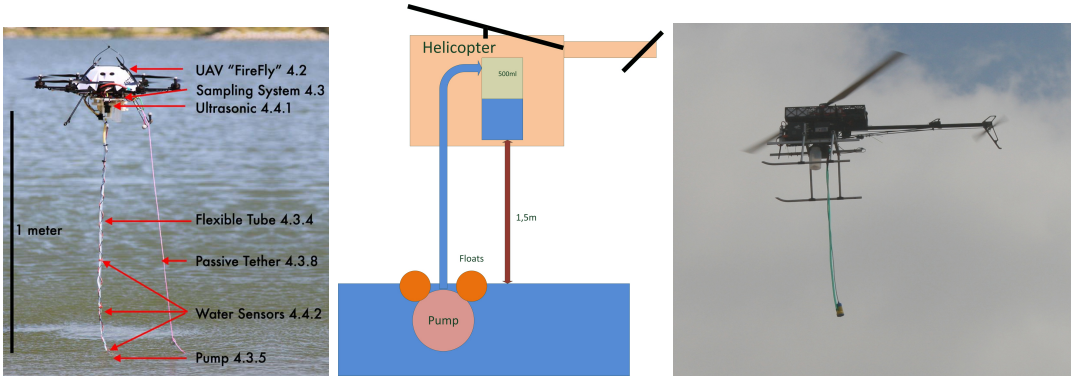


Figure 13: Most common UAV usage categories



(a) Approach of the drone and sampling bottle to the surface of Yugama crater lake [53]

(b) Photograph and schematic illustrations of the water sampling bottle. **a** Photograph of the water sampling bottle with size in mm, and **b** schematic illustrations of the bottle [53]



(c) Water sampling system with chapter labels [62]

(d) Principle of sampling [63]

(e) UAV with water sampling mechanism in flight[63]

Figure 14: Drones for water sampling

in a secondary time during the PhD, which was shorten to an MPhil, leaving relatively less time for this second part.

3 BADAS

3.1 What we want to do

For this part of the research, the focus is ported on these 3 points:

1. Long range flights: the need for long range comes from the fact that the drone is going to carry some payload from a distant location (the laboratory directly) to the sampling location. More range means more practical possibilities. An airplane type is therefore preferable for this requirement.

2. Short takeoff and landing: for taking-off and landing close to the lab, and in small body of water, a short takeoff and landing capability is required. An multicopter is preferable for this, as they can hover in place, and take-off and land vertically.

3. Underwater navigation: the sample of water should be taken at a specific depth (maximum 5m) in order to gather layered distribution of the water body. A submarine is preferable in this case.

As can be seen, the 3 points are contradicting each other, as airplane with hovering capability is only seen in acrobatics, and a multicopter with long range exists only by increasing the size of the drone and its battery life. The underwater part goes against the aerial parts, as underwater robots are more dense to be able to sink seamlessly.

3.2 Evaluation of existing drones

Based on section 2.1, three drones are evaluated to be used as a basis for the new platform, as none satisfies the 3 requirements.

3.2.1 SailMAV

SailMAV [28] is a platform based on a seaplane configuration. It can fly like an airplane, and land on the water as a seaplane thanks to its two floating hulls. The specificity of this drone is the capability to fold its two wings vertically and use them as sails.

It is designed with the intent of harvesting the power of the wind while at the surface of the water, making it a right choice for long duration mission at sea, and as a result can be embedded with sensors (microphone, wind-sensor, underwater camera) for oceanography or hydrology studies for example.

Using the same control surface for both air and water navigation is key in this drone to make it lightweight enough. This is a key for hybrid drones, as adding more motors and control surfaces can make the drone unnecessarily complex and not optimal for both media. As a result, the amount of redundant mass in flying and in sailing is less than 20%.

3.2.2 MEDUSA

MEDUSA, a Multi-Environment Dual-robot for Underwater Sample Acquisition [29], is a quad-copter modified to hold a submarine pod. It can land on the water thanks to the modified landing gear, transformed into flotation device, and deploy a tethered pod that can navigate underwater.

The pod has a depth control through the change of volume of an hyperelastic membrane, controlled with air pressure through the tether, as well as X-Y navigation thanks to 2 water-jets on its sides, making it swim like a differential-drive robot with an additional constraint. The speed of each jet cannot be negative, so the movement is limited to forward and turning.

The whole robot was designed specifically designed for water sampling in hard to reach location, as the pod can reach places that need underwater locomotion, while the drone can fly

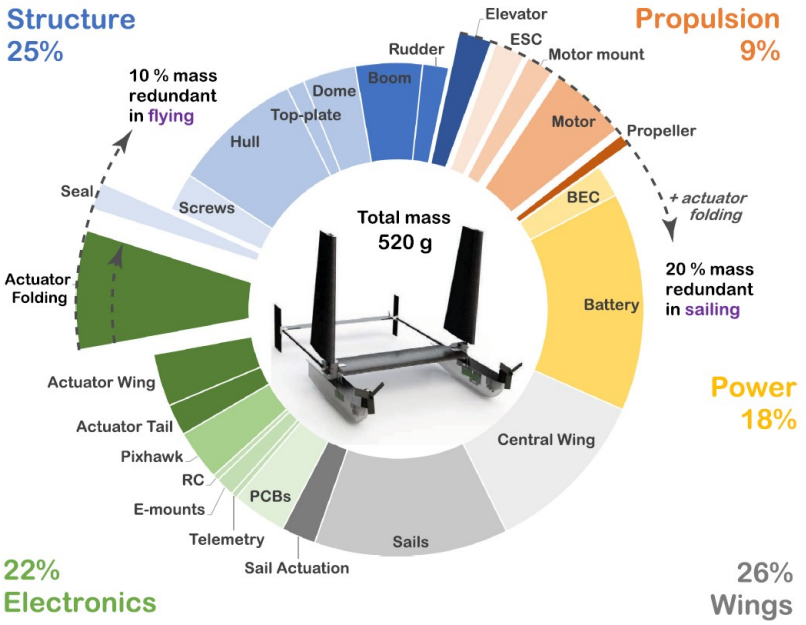


Figure 15: Mass distribution of SailMAV, split into five categories: structure, propulsion, electronics, power and wings. The exploded bars show the penalty associated with the hybrid design in both sailing and flying. Reproduced from[28]

from the shore to the water body. Sampling system can be added to the pod to gather sample faster than humans and without any risk.

It has however not be shown that the pod can carry water sampling equipment without changes, and being in the category of the quadcopters, the flight range is limited.

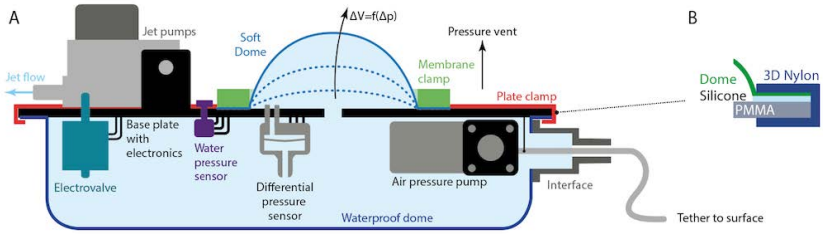


Figure 16: **A**. MEDUSA Pod schematic **B**. Sealing Clamp. Reproduced from [1]

3.2.3 AquaMAV

The AquaMAV [4] is a drone which is capable of long range flight, and diving in the water by folding its wings. The takeoff is done impulsively by using a jet propulsion method, propelling the AquaMAV from the water surface. In the airplane category, this drone is capable of doing water entry in depth and water exit.

The slender body of the drone is attached to a brushless motor with foldable propeller blades and servo-controlled foldable wings that are closed to make the plunge diving happen. The propeller has different speeds in water and air, thanks to a clutch gear mechanism that reduces the speed of the output when the motor is reversed. This is used to accommodate the difference of fluid density between water and air [64, 65].

The jet propulsion is used to have an impulsive take-off from the water surface to break off from the surface tension and generate enough speed and height until the propeller and wings

lift can take over and make the drone fly in the air.

However, it has to be launched by hand or from a launcher if launched from the ground, has no landing gear and has little to no payload available, which makes it impractical for water sampling activities. Scaling up this drone to add some payload is hard to do as the design of the propulsion system takes already a considerable weight. Additionally, due to it impracticability for landing and flying, it doesn't suit very well a scale up operation.

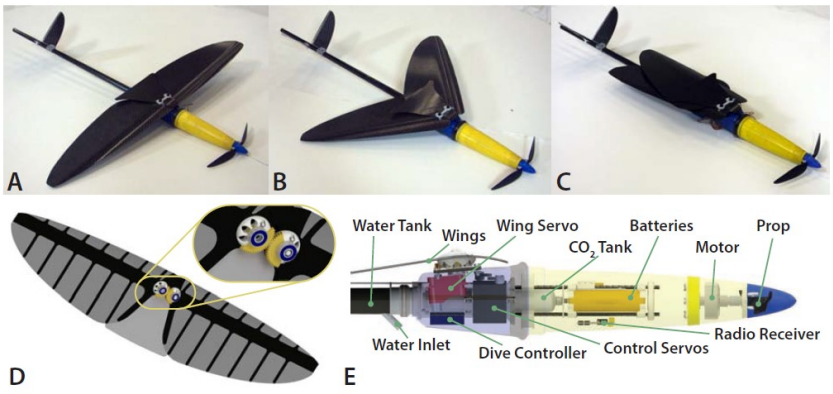


Figure 17: The AquaMAV airframe: **A-C** Fabricated prototype, shown with **A** wings open, **B** swept 45°, and **C** 90°backward. **D**. CAD rendering of the wings, showing the layup pattern and gear linkage. **E**. CAD illustration of fuselage, with internal components labelled. Reproduced from [66]

3.2.4 Summary

From those 3 drones, the MEDUSA and the AquaMAV have capabilities close to what is required: both are missing the actual water sampling capability, MEDUSA lacks long-range flights while AquaMAV lacks the usability and proper underwater navigation.

The SailMAV is also close to the requirements, but adding or modifying it to have underwater capabilities far from its purpose.

The AquaMAV is chosen here to be improved upon to be more practical and have more capabilities.

3.3 Selected platform and evolution

The AquaMAV has been developed originally by Rob Siddall between 2013 and 2019, and has been further developed by Yufei Jin until 2020, identifying weaknesses and possible improvements.

3.3.1 2017

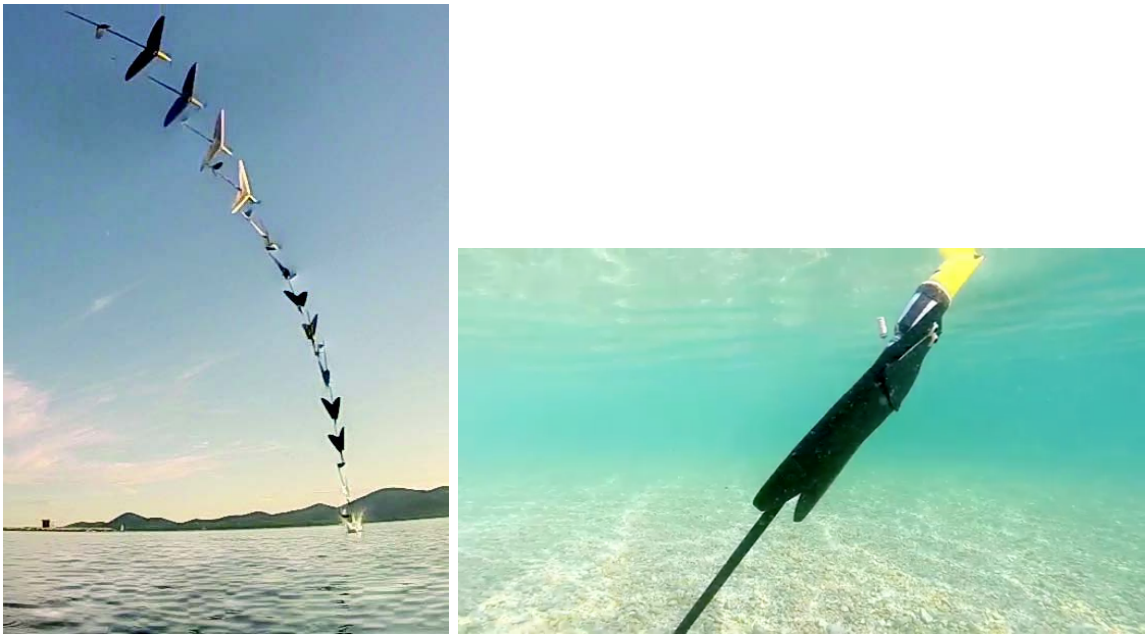
The original AquaMAV drone is created by Dr. Siddall during its PhD research[66]. It has foldable thin wings, a single propeller and a v-tail for flight control, and uses a CO2 cartridge as power source for the water jet propulsion in order to take off from the water.

It was made as a proof of concept that such a drone could be made, but had a few weakness, as shown on the following figures.

Figure 18(a) shows the AquaMAV during its plunge diving phase, where it rolls a couple of times over itself while diving, which shows an uncontrolled dive. This comes from the small control surface of the v-tail which cannot compensate the loss of stability that the wings where giving, in addition to the propeller induced torque and the torque induced by folding the wings.

Figure 18(b) shows the AquaMAV just before water take-off. It is observed that the drone is laying on its back, making it taking-off in an non-regular position, instead of from its ventral position. On the flight, it will therefore have to do an 180 degree roll to return to a stable flight situation.

A 3rd problem was identified to be a thin wings issue. Due to the way the wings are designed, they are behaving as a bistable mechanism where they are, most of the time, in the shape of a wing, but when the wind increased, they would fold onto themselves deforming, and would not generate lift anymore.



(a) Plunge diving phase

(b) Water take-off phase

Figure 18: AquaMAV diving and take-off [66]

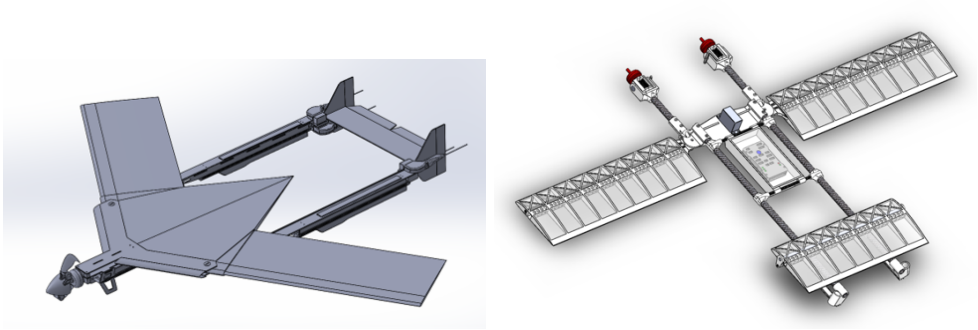
3.3.2 2019

Multiple prototypes where created thereafter to solve the different problems by Yufei [67].

The 1st one has thicker wings and bigger surface control on the tail (Figure 19(a)) to avoid the wings bending and the loss control during the dive. The 2nd iteration tried to position the Centre of Gravity (CoG), Centre of Buoyancy (CoB) and the Aerodynamic Center (AC) to improve the ventral position on takeoff and flight performance. This was done by splitting the body from a single slender fuselage to a two-tail body in order to move the weight and buoyancy volumes as needed (Figure 19(d)). The 3rd design was made by adding a 2nd propeller, rotating in the opposite direction of the first one to improve stability on diving, as seen in Figure 19(b). The last design changes where added, changing the wings from thick-filled wings to thick-hollow wings with a proper airfoil section, improving the buoyancy of the drone and its wings lift coefficient, and changing the tail control surface to thrust vectoring propellers, allowing to control the multicopter. The CAD is shown in Figure 19(e), whereas a prototype was made and can be seen in Figure 19(c).



(a) Thicker wings (b) Diving and take-off stability (c) Prototype



(d) CoG, CoB, AC positioning (e) Hollow wings bicopter

Figure 19: AquaMAV design iterations

3.4 Design of the BADAS

The Bicopter Aerial anD Aquatic System (BADAS) design is mainly inspired from the latest design from Yufei (2020). Indeed, such a design has a lot of different capabilities and could therefore be working for many different applications. We are going to explore each design properties of the platform and analyse them. Here is a preview of the characteristics that are detailed in the next sections.

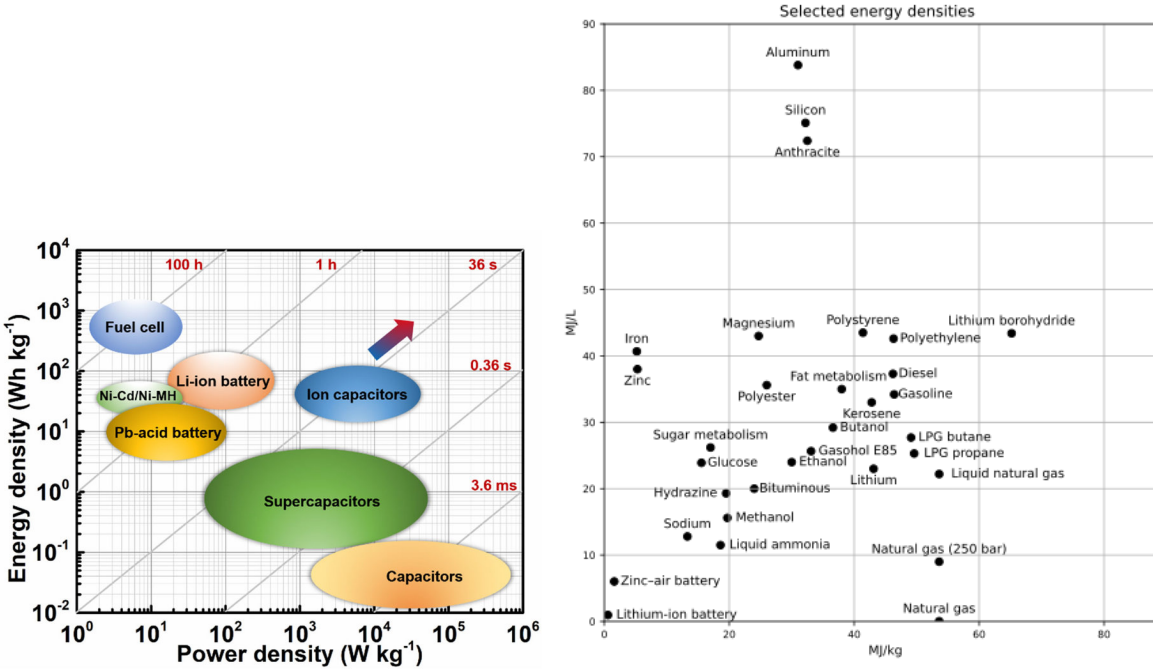
- Dual thrust vectoring propeller: such a configuration allows the drone to be controlled as a bi-copter, a quadcopter with only 2 propellers.
- Vertical Take-Off and Landing: being controlled as a bicopter, the take-off and landing stage from the ground and water can be vertical, allowing precise landing for delivering samples.
- Airplane mode: having wings allows for long flight, longer range mission, which means that the water sampling mission can be launched further away from the sampling site.
- Plunge diving: inspired by nature, the wings can be folded, making the drone diving in the water, using the height of the drone to go deeper faster.
- Hollow wings: the wings are designed in an uncommon way, being made from a hollow structure covered with a thermoplastic sheet to generate the airfoil profile.
- Aerodynamic: the flight characteristics are defined here, leading to a biplane wing configuration for a drone of a short length.

- Centres position: CoG, CoB and AC positions are evaluated and moved to fulfill the need of flight characteristics and buoyancy.
- Mechanics: design choices on some of the mechanical components.
- Electronics: the choices of the electronics components that allowed the drone to be assembled into a working platform.

3.4.1 Dual thrust vectoring propulsion

The propulsion system of a drone is what allows the drone to gain speed and move in the space. There exists many different solution for a drone [68], using different energies and mechanical components.

The choice for quadcopters or planes of medium size is to use electric brushless motors with Lithium-Polymer (LiPo) battery. They offer compact size, low weight and inertia, high rotational speed and low latency speed control which is very important for stabilizing a drone in hovering flight. Indeed, the control is mainly done by changing the speed of the motors precisely and quickly enough to react to the control law. The LiPo battery provides an efficient energy storage for their size and weight 20(a). Using fuel-based storage has not yet reached its full potential for small drones as the motors and mechanical components for driving fuel-based motors are heavier than electric ones. However, LiPo have a quite poor energy density compared to some other energy sources 20(b). If scaling up the size and weight of the drone, consideration should be made for other technology that will likely be more efficient than LiPo for energy storage. There is a large choice of brushless motors and batteries to choose from based on the final weight and flight duration that will be needed, as many drones are nowadays using these technology [69, 70].



(a) Power density vs Energy density for common battery systems [71]

(b) More general energy density [72]

Figure 20: Comparison of power and energy densities

An important note for brushless motor is that they are waterproof by design. Indeed, they don't have any integrated circuits in them directly, the coils are non-conductive on their exterior

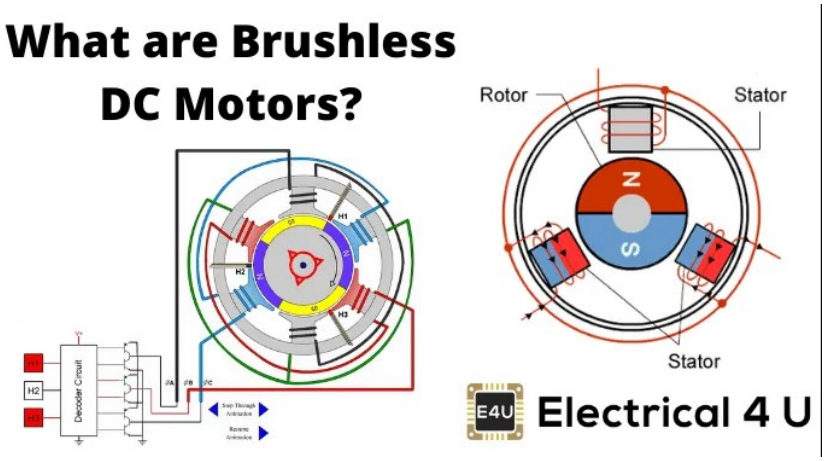
parts, and as they are not using any brush (in contrary to brushed motor), there is no physical contact where water could do short circuit. The only parts to waterproof carefully are the electric wires used to connect to their Electronic Speed Controller (ESC), which can be easily done using special but common waterproof heat-shrink tubes.



(a) Example of an RC Brushless Motor 2212 1000KV from [73]



(b) Rotor and stator components of an out-runner brushless motor [74]



(c) Schematic of the electrical components of a brushless motor [75]

Figure 21: DC brushless Motors

In addition to choosing the motors and the battery, there is many configurations in which these motors can be mounted. This is seen, for example, by the number of different airframes that are supported by a flight controller (PX4 currently supporting about 30 different airframes [76]). The number of independent motors that are needed depends on the Degree of Freedom (DoF) that the drone can have. In our case, and in most cases for drone locomotion, 4 DoF are required, which is enough to do most of the locomotion needed in the 6 DoF that can be reached in the 3D space, x-y-z positions and roll-pitch-yaw angles. The 4 DoF are usually roll-pitch-yaw-z for drones, and roll-pitch-yaw-x for planes.

Therefore, only 4 motors are needed to control drones, which is why most current drones are quadcopter, with 4 propellers. However, The combination of 4 motors can widely vary. There is the need for a thrust generating motor (called propeller hereafter) and some other motors (called servo hereafter), which can be servo-motor, redirecting the thrust generated by the propeller. they don't generate thrust but are used to modify the direction of the thrust or modify the aerodynamic properties of a control surface, generating some control force. We can choose a

combination of propeller and control summing to 4 to create any drone capable of 4 DoF.

Props	Servos	Airframe	Remarque	Figure
1	0	Ball drone	no full control	22(a)
1	3	helicopter	compensation of induced torque needed	22(b)
		airplane	ailerons, elevator and rudder	22(c)
2	2	bicopter	servos controlling its thrust direction	22(g)
		airplane	with ailerons only	22(e)
3	1	tricopter	servos controlling the direction of the back propeller	22(d)
4	0	quadcopter		22(f)

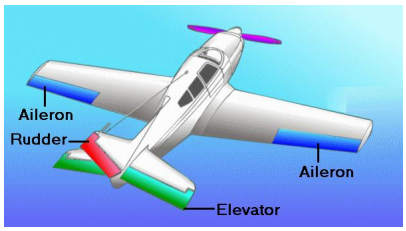
Table 1: Configuration of propellers and servo



(a) Ball drone [77]



(b) RC helicopter [78]



(c) Plane control surface [79]



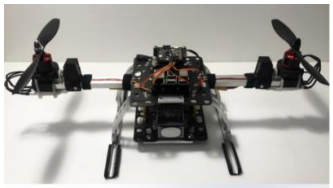
(d) Racing tricopter from Lucidcam [80]



(e) Wingtra One for mapping and survey[81]



(f) Quadcopter [16]





(g) Designed bicopter & 3D modeling. Reproduced from [82]

Figure 22: Thrust generation on different airframes

We can see on this exploration that the combinations of 2 propellers and 2 servos can generate an airframe which has similar configurations in copter mode and in airplane mode. Indeed, using either the bicopter configuration, where the 2 servos are used to control the direction of the thrust, or the airplane with ailerons, where the thrust is projected directly on the control

surfaces, we can have an airframe that can switch between airplane and copter mode and be optimal in both flight mode.

This first exploration of the propulsion system gives us a minimum number of motors for the same DoF as a standard quadcopter and airplane, and combination which can be used seamlessly in airplane or in copter mode.

3.4.2 Vertical Take-Off and Landing

Vertical Take-Off and Landing (VTOL) is the characteristic by which a drone can do a take-off and landing vertically. This seems trivial when taking about copters as their design is essentially hovering, so they are VTOL system by conception. This is more interesting when looking at airplanes, as one of their issue is the need for a runway for take-off and landing, which then necessitates a landing gear, which can be quite complex.

Many different system have evolved to create VTOL airplanes, as seen on Figures 23(a), 23(b) and 23(c), but as it can be observed, they simply added more motors to add the VTOL capability to an existing airplane, usually called quadplane. Military airplanes have also been developed with tilting rotor in order to use the same propulsion system in VTOL and in airplane flight. For those system, the orientation of the their body with respect to gravity is not changing, in the sense that they are taking-off in a given orientation of their main body frame and don't change it while the transition happen between take-off and flight.



(a) Mini Convergence VTOL BNF Basic, 410mm [83]



(b) Griflion H VTOL [84, 85]



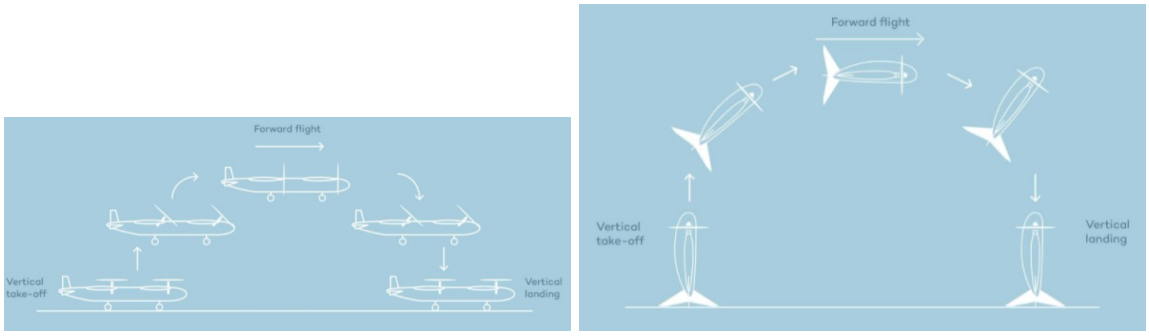
(c) An MV-22 used during a MAGTF demonstration during the 2014 MiramarAir Show [86]

Figure 23: Different VTOL systems

A interesting concept for VTOL are tailsitters. Originating from 1920 with Nicolas Telsa [87, 88], they are airplanes that take-off and land on their tail, and pitch forward and backward when transitioning to flight. For airplanes in which the pilot is actually physically present, they have the disadvantage that the pilot changes its orientation and has no visibility while in vertical orientation, which is impractical for landing precisely. However, in a UAV, this problem doesn't arise, as it is autonomous. The advantage of tailsitter over VTOL is mainly the reduced complexity of the mechanics, as the range of movement of the control-servo, controlling the direction of the thrust, can be greatly reduced.

There are 2 ways of building a tailsitter: either thrust vectoring, where the propeller motors are moved, or ailerons control, where the thrust motors are fixed, and the air flow they produced always reaches a control surface which are the ailerons. In thrust vectoring, the thrusters can be either at the front (pulling) or at the back (pushing) of the drone. Pulling is dynamically stable, while pushing is inherently unstable. In the pulling situation, the drone is "hanging" below the propeller, which makes it stable.

We decided to keep the thrust vectoring design of the previous version because the control system is not dependent on other part of the drone, which could be hidden by other moving parts of the drone (wings folding for example). The drone will therefore be a bicopter tailsitter,



(a) "A VTOL quadplane drone looks and flies like a conventional plane, and has an unconventional vertical takeoff and landing ability" [89]

(b) "A tailsitter drone like the VTOL WingtraOne lands and takes off from its tail, and tilts in the air to enter forward flight mode" [89]

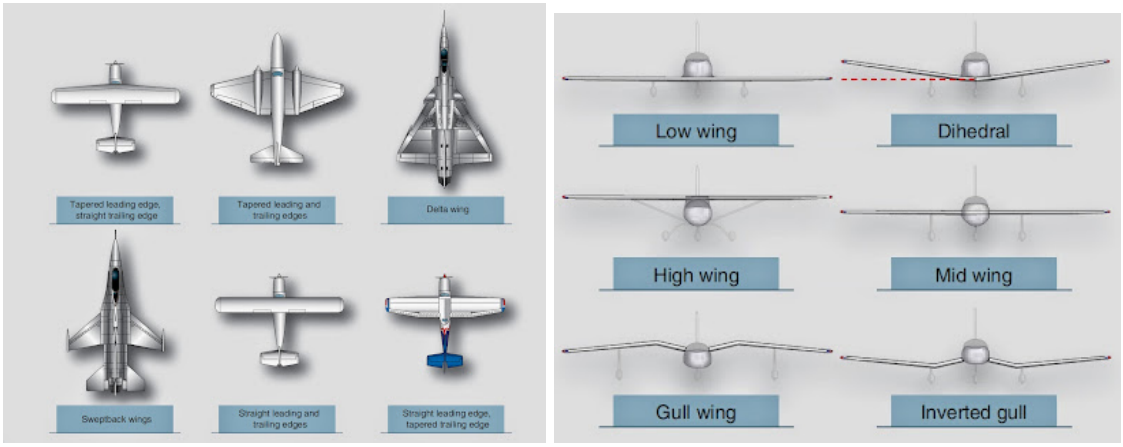
Figure 24: VTOL vs Tailsitter schematic

with no control surfaces, other than the tiltrotors pulling the drone.

3.4.3 Airplane and underwater constraints

The drone is supposed to be inspired by airplanes for its shape, meaning that it should have wings, a required component for long range flight, while also being as dense and packed to be able to navigate underwater.

Aircraft wing configurations are various in size and shape to provide different flight characteristics at different speeds, different amount of lift and stability.



(a) "Various wing design shapes yield different performance" [90]

(b) "Wing attach points and wing dihedrals" [90]

Figure 25: Wings configuration on airplane

For an airplane with longer autonomy, that still has to be controlled by human pilot, a configuration with longer, slow-speed wings is advantageous. Delta wings or swept-back are intended for higher speed airplanes. To make it feasible for bicopter, the body of the airplane should be wide enough to have 2 propellers in front. Propellers cannot be put on the wings directly due to the water entry requirements (see next section 3.4.4).

For underwater, the drone must have a more compact shape to reduce skin drag and turbulence that could damage the long wings when swimming, the shape being taken in the moving

direction of the drone. Therefore a Delta wings or swept back wings look more promising, as they more aerodynamic and compact.

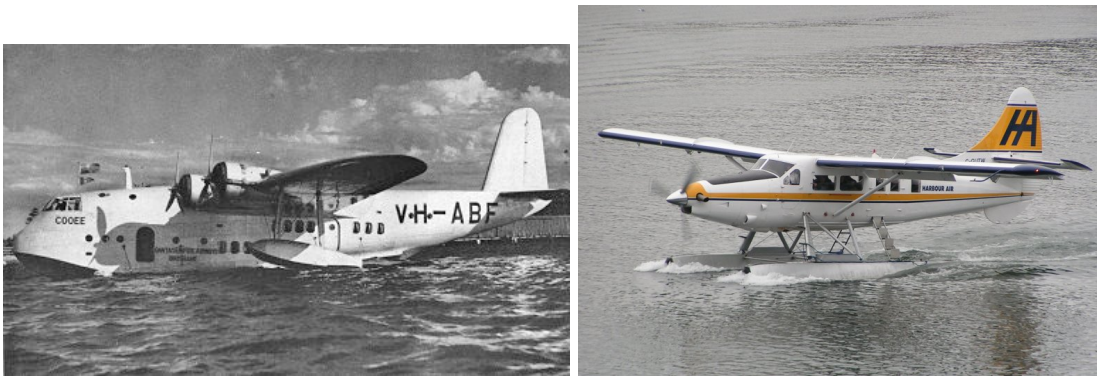
3.4.4 Water entry

Water entry forces have been studied since 1929, and more currently studied for projectiles and UAVs based on their angle of attack [91, 92, 93]. The important result of these research results are that the shape of the object entering as well as its angle of attack are the most important to get a proper entry. In our case, a proper entry is one with great depth, and no breakage of any part of the drone. This can be done in 3 ways for a drone:

1. Landing on water by hovering: In this case, the drone simply hover over the water and gradually reduces his altitude until landing at the surface. It can then shut of the power of the thrusters and deepen himself in water. This is a safe way with a controlled water entry and very small forces on the body of the drone, as the entry is made gradually, slowly.

2. Landing on water by gliding: This method is commonly used by seaplanes (floatplane (two floats below a plane - Figure 26(b)) or flying boat (where the plane body fuselage is used as a float - Figure 26(a))) to land on the water thanks on their float. They reduce their speed and altitude to land by gliding on the surface until stop is reached.

3. Plunge diving: This method, mainly used by hunting birds, consists of a dive from higher height, closing their wings and diving head and beak first in the water to catch their prey. They break the water surface at high speed to surprise their prey, not leaving any time for them to react (Figure 27). As reported by the studies, the forces in action are much more stronger in a dive like this [94], but result in a deeper depth and a better energy transformation from height to speed to depth.



(a) Short S23 "C" Class or "Empire" Flying Boat [95] (b) Floatplane DeHavilland Single Otter Harbour Air [96]

Figure 26: 2 different system for landing by sliding

The current design choices that we have allow for two of those methods, the landing by hovering, and the plunge diving. The hover-landing is a safer way of doing the water entry, having less risk of breaking any components of the drone. It is however slower and more subject to wind burst close to the surface of the water.

Plunge diving in the other hand is a faster, more dynamic method, but requires a mechanism to close the wings to make the body streamlined in order to not break part further away for the body-fuselage of the drone, where the wings are attached. This is already planned in order to have a streamlined body underwater. Plunge diving can also imply a loss of passive control, as



(a) Kingfisher hunting [97]



(b) Gannet (Morus bassana), Belmont [98]

Figure 27: Plunge diving birds

the wings (main flight stabilizers) are getting closed while diving. Therefore an external control should be looked for in order to close the wings as late as possible, keeping the control longer. This can be done with optic flow.

Optic flow is a method that is used to calculate velocity of object based on their movement in view plane of the observer. It is defined as "the change of structured light in the image" [99], when seen on the retina or image plane of the sensor. In correlation with the Tau-effect [100, 101], "the reciprocal of the time-to-contact can be obtained from the optical flow divergence (OFD)" [102]. This Time-To-Contact (TTC) is a variable that is used by seabirds when diving in order to close their wings when needed, as it estimates the time remaining until contact with the water surface [103].

Controllers based on optic flow can be used to estimate the TTC to textured surface, to keep a fixed position relative to it, or to reach that surface with a null terminal speed. This is used in autonomous landing for quadcopter as it provide a smooth controller output and is quite easy to implement using constant OFD control loop.

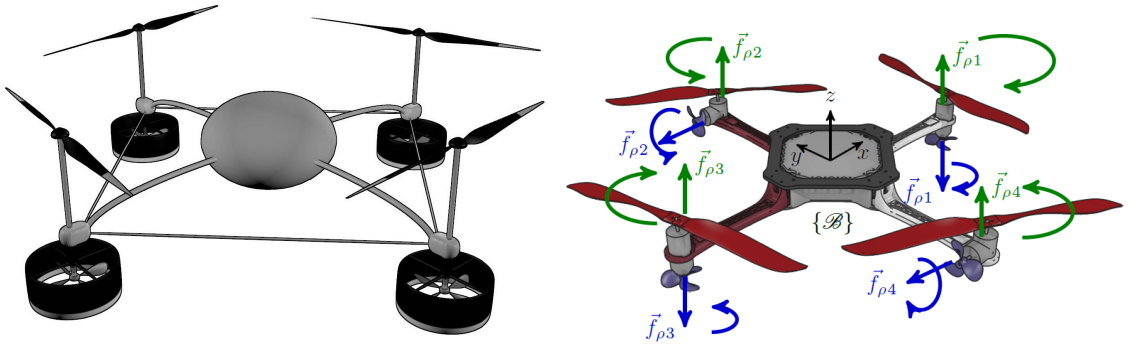
3.4.5 Water exit

Leaving the water is another complex task for a drone. It can be done gradually, doing an incremental pull out of the water, or dynamically using an impulsive power, using a jet for example [104, 7]. The differences include duration of take-off stage, ability to control during that stage, intensity of forces in action, robustness to sea state.

Impulsive take-off through the water surface can be done using a jet-propulsion method, as in [105]. Using a compressed C02 cartridge or more complex chemical reaction [106] to create a impulsive water-jet, drones can take-off from water rapidly and have water-air transition time as short as possible, reaching the cruise speed for an airplane very efficiently. This is an efficient method for airplane types of drone that require a high cruise speed to maintain lift, but requires a non-negligible additional weight to carry a reaction chamber strong enough to sustain the pressure needed to push the water and resulting in a powerful jet.

A slow gradual takeoff can be done for example with a drone whose propellers are out of the

water, turning them on, slowly pulling the drone out of the water. This has one pre-requisite which needs to be tackled while designing the drone. To fly, the air-propellers need to be spinning at high speed in the air, avoiding contact with water, as at high speed, this can slow them down or might even damage them. In order to have the propellers out of the water first, the drone need to either be positively buoyant which has to be regulated [107], or need to constantly thrust to keep the drone afloat [108, 109]. This is done by some systems that use multiple pairs of thrusters, air-propeller and water-propeller, turning at different speed to push the drone through the water surface with the water-propellers until the air propellers can start freely spinning at high speed.



(a) "A proposal design for our Hybrid Unmanned Aerial Underwater Vehicle (HUAUV)" [108]

(b) "Forces and moments generated by the propellers of the HyDrone: green arrows represent the aerial operation, while blue arrows represent the underwater operation." [109]

Figure 28: Hybrid UAVs

In our case, the design choices made so far are pushing towards the slow transition as the drone is capable of hovering and will be made slightly positively buoyant. As the control of the drone is made by the tiltrotors, almost full control will be regained as soon as the drone starts getting out of the water. This would not be the case if using the "ailerons" control scheme (see Section 3.4.2). Indeed, in the second case, the control surface would not be able to adjust the thrust direction as long as the body of the drone remains partially in the water.

3.4.6 Wing design

Wings can be made out of a lot of different material and design. To make them light, early wings were made from a fuselage on which a lighter skin material was added. The fuselage was made to be a lightweight structure on which the skin could be attached or fixed, filling the voids, increasing the surface to create air resistance. This was adapted to bigger airplane with stronger material, but the schema is the same: a inner strong structure giving the overall shape of the wing covered with a lighter skin material acting as the exterior surface in contact with the air.

Another way to manufacture wings is to cut them directly out of dense foam. Foam is indeed a very lightweight material which can keep a given shape easily. A few reinforcements are added to prevent the foam from degrading too fast (skin around the foam, or added spar or ribs).

One of the important differences between these 2 methods is the volume of material that is used. When using a foam wing, the principle is that the wing, being fully composed of foam, will keep its shape as the whole volume is occupied, therefore deformation cannot occur easily. In the other hand, using a inner structure with ribs and spars make the inner of the wing hollow.

This difference is important when the wing has to be put in water, as it's buoyancy is determined by the volume occupied and the weight of the wing. In general, both methods will

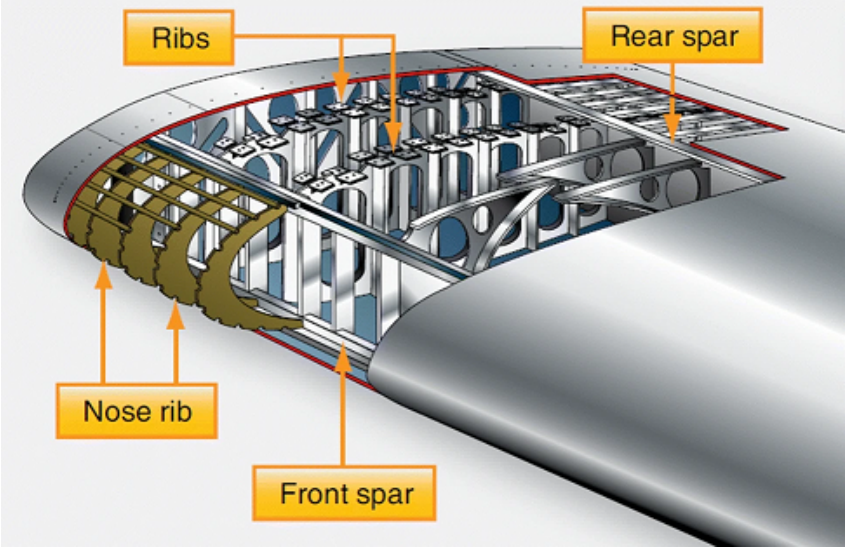


Figure 29: Nomenclature of a wing structure. Reproduced from [110]

generate a wing with the same volume of moved water when immersed, because the structured wing is closed, no water can come inside. However, by allowing water to enter and exit the wing, the volume of water that is moved can be greatly reduced to simply the sum of the volume of the spars and ribs, instead of the full volume of the wing.

We can compare 3 different wings that could be used for a drone platform.

	foam wing	**hollow wing**
material	RPUF	ABS
external volume	47.71cm3	47.71cm3
weight	7.64g	3.75g
dry density	0.16g/cm3	1.02g/cm3
volume of water moved	47.71cm3	3.68cm3
mass of water moved	47.71g	3.68g
in-water density	-0.84g/cm3	0.02g/cm3

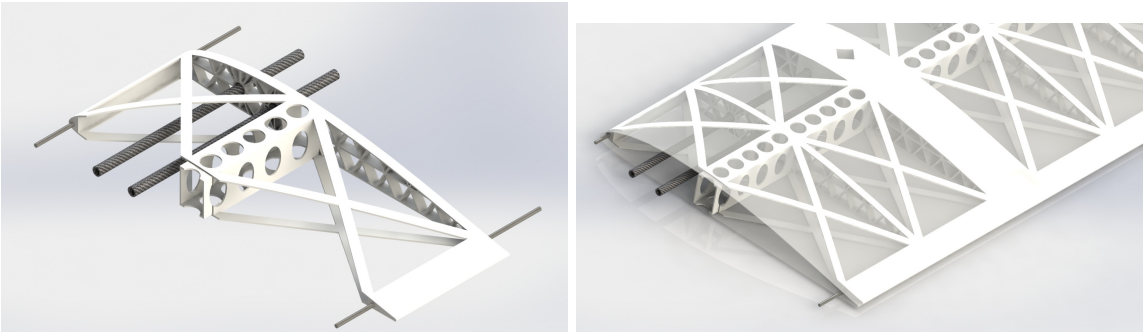
Table 2: Comparison of foam wing and hollow wing density

We can see that a hollow-open wings can be made out of solid plastics material for the ribs, additional strong spars and a plastic skin sheet, with a "in-water density" of 0.02g/mm3, which means the wing is neutrally buoyant. This is quite important as the wing represents the second of the biggest volume of the airplane, the first one being the body.

3.4.7 Aerodynamics

We now have the possibility to calculate the main dimensions of the aircraft needed for flying. The important parameters will be finding the wings and tail dimensions based on the cruise speed and weight of the drone. The weight of 800g is based on a previous version estimate and the cruise speed of 10m/s is based on what other planes of the same weight can do. After choosing an airfoil profile for low speed flight (S7055 [111]), the wing surface be chosen to generate enough lift to carry the airplane. The span and chord length can after that be chosen to satisfy other mechanical constraints.

Using a standard plane configuration with straight wings, this leads to a single wing surface of 0.096 m2. In order to choose the aspect ratio (AR), which is the wing span over chord length, different parameters have to be taken in consideration. Long wings with high aspect ratio have a



(a) Single rib of the BADAS wing (b) Wing assembly of the BADAS

Figure 30: Detail of the ribs on the BADAS

better lift-to-drag ratio, so a longer wing will improve endurance. However, for longer wings, the structural bending will need to be supported by stronger carbon fiber spars. An important factor is that once the wings are folded, the entire drone should still be slim enough for underwater navigation. For these reasons, the aspect ratio was chosen to not go below 3 for a single wing.

$$\text{dynamic pressure} : q = 1/2\rho v^2 \tag{1}$$

$$\text{lift} : L = C_L \cdot A \cdot 1/2\rho v^2 = C_L q A \tag{2}$$

$$\text{drag} : D = C_D \cdot A \cdot 1/2\rho v^2 = C_D q A \tag{3}$$

$$\text{drag coefficient} : C_D = C_{D_0} + \frac{C_L^2}{\pi e AR} \tag{4}$$

$$\text{Aspect ratio} : AR = b/c \tag{5}$$

$$\text{Wing surface} : A = b \cdot s \tag{6}$$

where:

ρ = air density
v = speed of the air on around the wing
b = chord length
s = wing span

This led to a choice of long wings of 0.8m span and 0.12m chord length, with AR=6.6. However, having long wings like this turned out to be problematic for the body of the drone and for the folding torque required. As long wings have a bigger inertia, the torque required to fold them increases. Long wings also imply a longer body to be able to fold the wings completely. The 0.8m wings span would require a drone of a length about 1m. This was developed and tested in the lab and resulted in a drone with a fuselage too fragile for its weight, breaking easily on takeoff.

As a result, the drone length needed to be reduced to 0.5m length, and with it the wing span to 0.4m, which also meant to increase the chord length to 0.24m, which was going to be too thick for the width of the drone. One solution is to use a biplane configuration.

Using 2 wings on each side, the lift can be increased by a factor 2 and the drag by 1.5 while keeping a higher aspect ratio wing. According to [112, 113], the Munk factor k is 1.24 with a gap between the wings equal to a chord length, and the induced drag can be calculated to 0.056.

Now that the wing has its dimension and a biplane configuration, their positions are designed to allow a drone as compact as possible by having the wing folded on the whole length of the drone. This is done by moving the center of rotation of the folding outside of the wings, as shown in Figure 33. The design is made to have a minimum clearing in between the wings when folding, to have a drone width as small as possible.

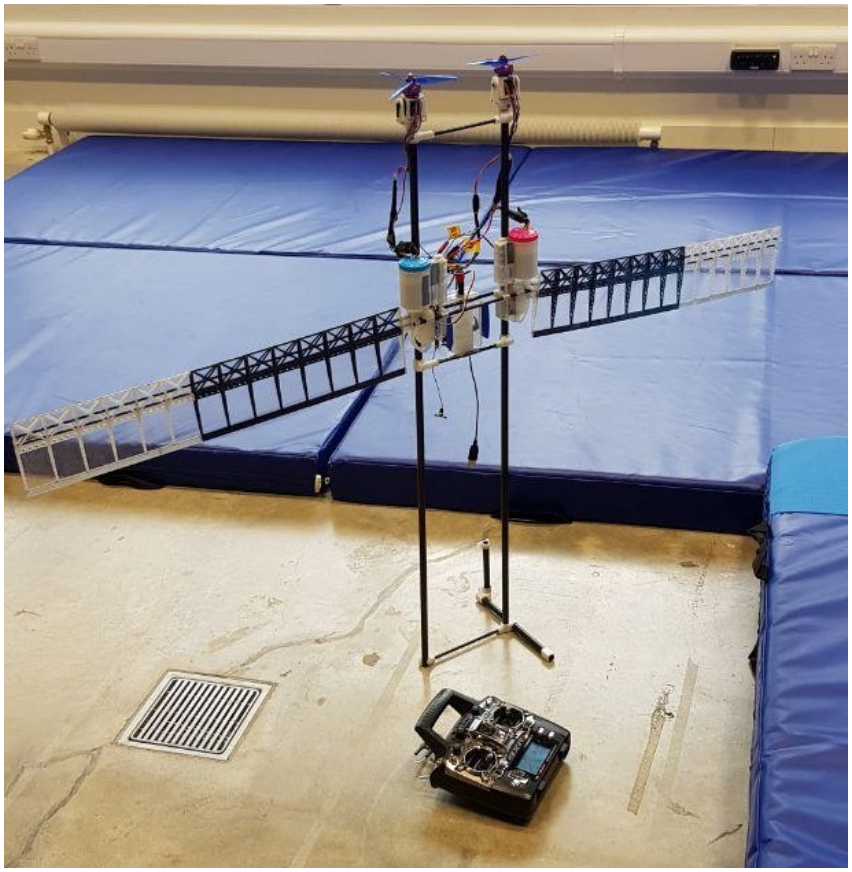


Figure 31: 1m long version of the new BADAS

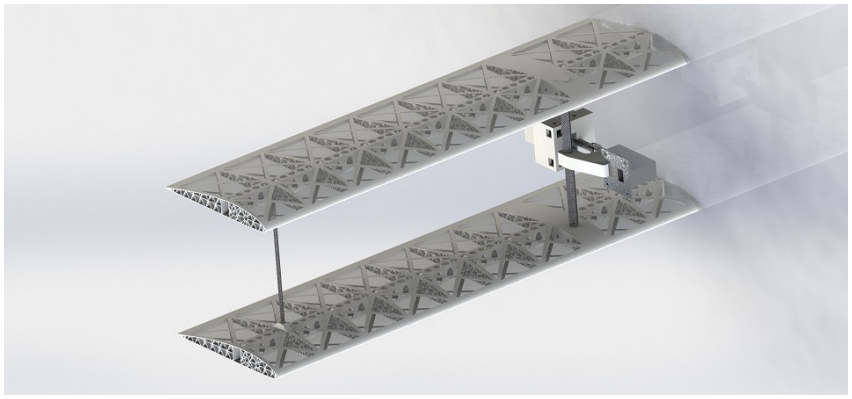


Figure 32: CAD of the biplane wings

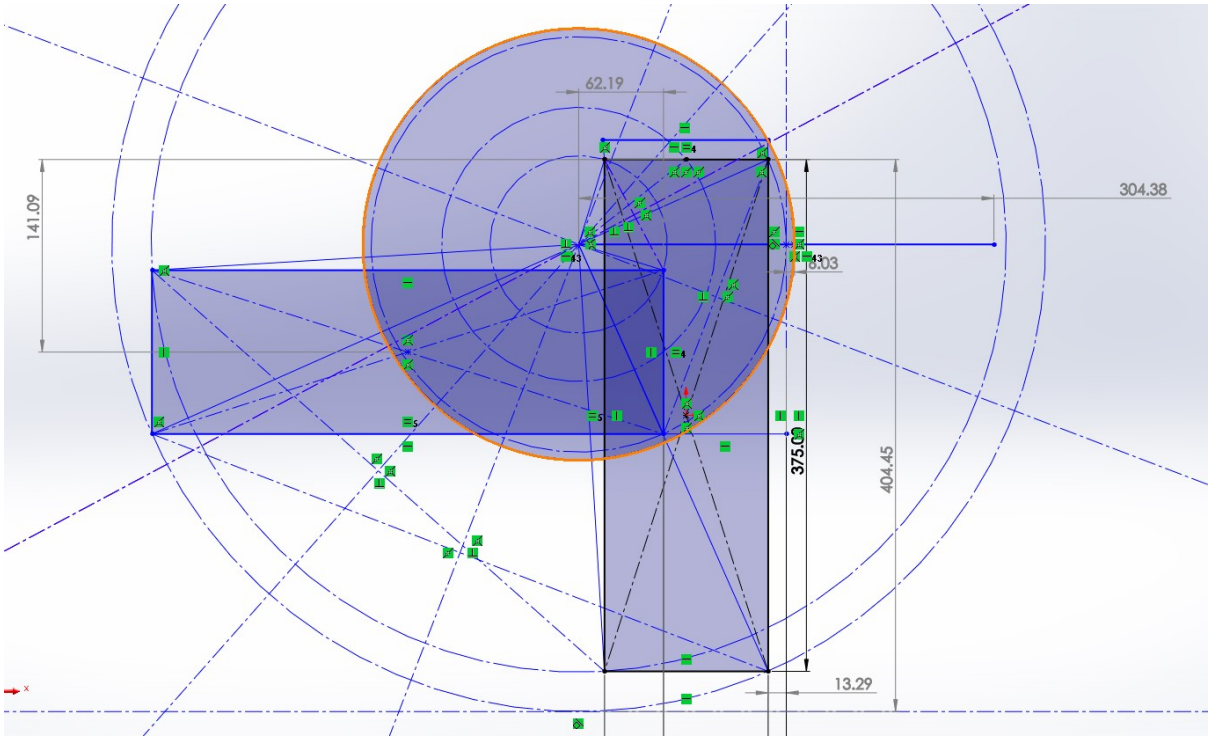
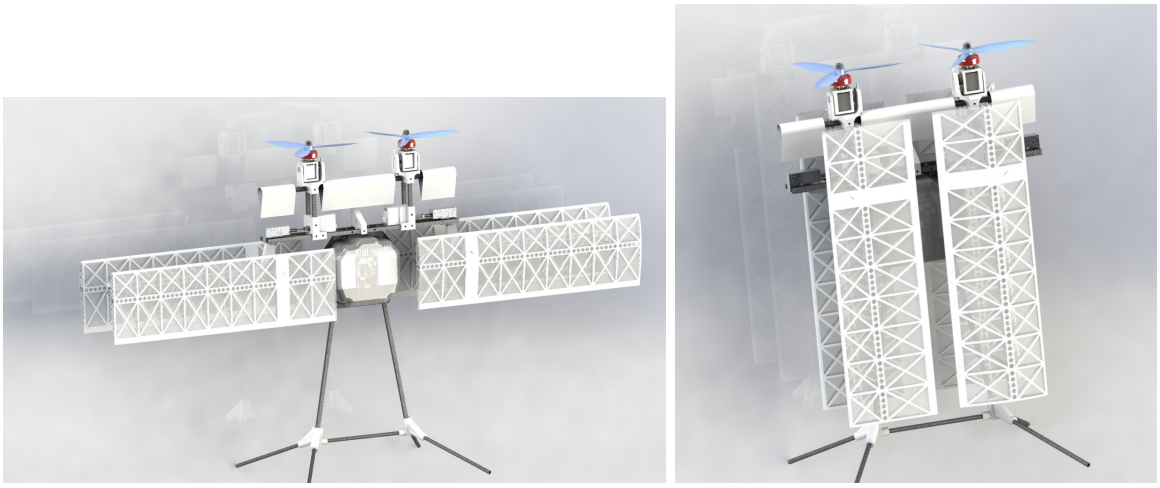


Figure 33: Schematic of the wing folding to dimension the wing span and chord length



(a) Open wings configuration

(b) Closed wings configuration

Figure 34: Configurations of the BADAS for flying or hovering and diving

3.4.8 Position of aerodynamic centres

For longitudinal static stability of a tailless airplane, with a Lift Coefficient (CL) positively linked with the Angle of Attack (AoA, or α) the CoG must lie ahead of the Aerodynamic Center (AC). Without a tail, the AC of the drone is determined mainly by the wings AC, which therefore will depend on the position of the wings along the body. The wings position is determined by the folding mechanism, and the CoG can be adjusted by moving some mechanical and electronic components.

Similarly for the buoyancy, the underwater stability must be determined in order to make the drone orient itself when no control is applied. Two stable orientations can be chosen, either horizontal or vertical. In the horizontal orientation, the drone will require less power to navigate underwater, as it will already be aligned with the direction of movement. In the vertical orientation, the drone will be ready for taking off from the water, going upward. This situation is preferable as the take-off is slightly more complex than underwater navigation.

To address the underwater stability, the concept of buoyancy is explored to make a proper analysis. Buoyancy is the force exerted by the fluid in which a body is immersed. It goes in the direction opposite to the gradient of pressure of the fluid, which in general is the direction opposite to the gravity force. The intensity of the buoyancy force is given by Archimedes' principle,

$$F_b = -\rho g V \tag{7}$$

where:

ρ = fluid density
g = acceleration due to gravity
V = fluid volume moved

Here is defined the concept of buoyant mass, which is simply the mass of the fluid being moved by the object immersed in the fluid.

$$m_b = \rho V \tag{8}$$

This can be used in the Computer-Aided Design (CAD) of the drone to compute the Centre of Buoyancy (CoB), which similarly to the CoG, is the centre of the mass of water moved by the immersed parts of the drone. Indeed, the F_b will apply on that CoB, in the same way gravity applies on the CoG. The CoB for the mass moved is the same as the CoB for the volume moved, but the CAD software used doesn't compute volume center, but mass center only. To calculate the CoB in the CAD directly, all the parts were modified to be a filled volume of water, representing the exact amount of water mass that they would move underwater. In addition, parts that would be inside other, therefore not participating directly to moving water, would not be taken into account.

This allows to compute the total mass of water that the drone would move underwater and its CoB. The stability can be analysed using the following equations based on Figure 35:

$$(\overrightarrow{W} + \overrightarrow{F_b}) \cdot \overrightarrow{e_z} = m \cdot g - m_b \cdot g = (m - m_b) \cdot g = m \cdot a_z \tag{9}$$

$$(CoB - CoG)_{(x,y)} \cdot m_b \cdot g = I_{(x,y)} \cdot \alpha_{(x,y)} \tag{10}$$

Equation 9 is Newton's laws of motion applied to forces on the earth-fixed z-axis, vertical pointing up. It shows that if the mass of the drone is more than its buoyant mass, it will sink, as expected. The target is therefore a buoyant mass slightly above the actual mass of the drone, to have a slight positive buoyancy.

Equation 10 is the Newton's laws of motion applied to torques along the earth-fixed x or y axis, applied at the centre of gravity, with CoB-CoG the distance from the CoG to the CoB.

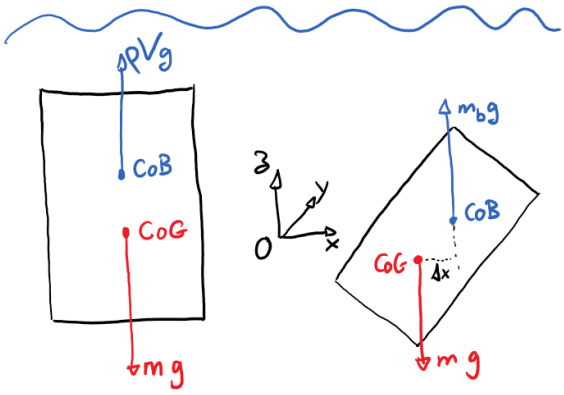
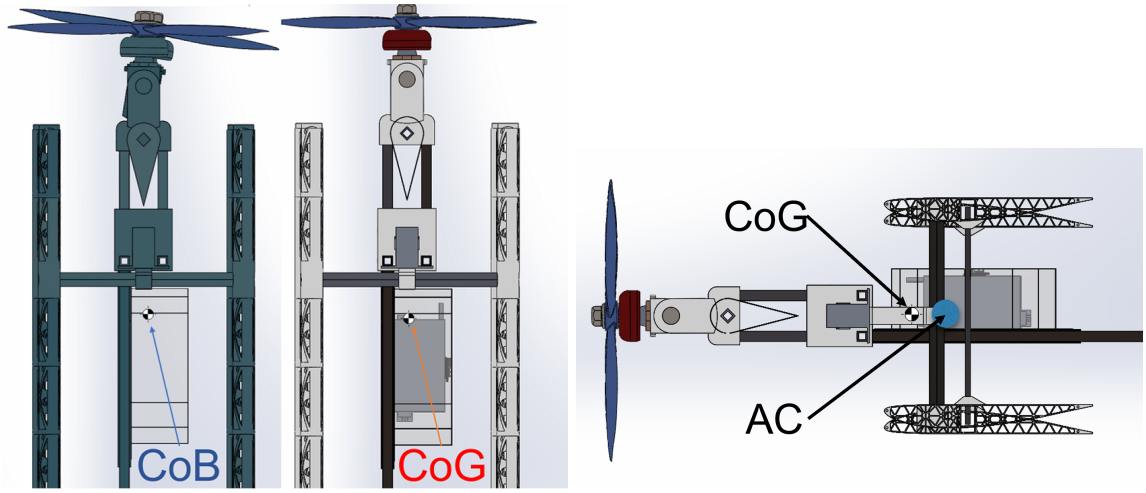


Figure 35: Schematic of the forces applying underwater

It shows that the drone will rotate around the x and/or y axis as long as the distance CoB-CoG projected on those axis is not 0. The CoB will therefore have 2 equilibrium positions, one above and one below the CoG in the z-axis, the first one being a stable position, the second one unstable.

To have a drone in a vertical stable orientation, the CoB must lie in front of the CoG along the forward direction of the drone, so that the torque stabilizes it in a vertical orientation.



(a) Position of CoB and CoG in closed wings configuration

(b) Position of the AC and CoG in open wings configuration

Figure 36: Position of CoG, CoB and AC

In Figure 36(a), we can see the estimated positions of CoG and CoB in closed wings configuration, which is the underwater configuration, while Figure 36(b) shows the AC and CoG while in flight configuration, with the wings open. From the nose of the BADAS, the distance to those centers is found to be 20.3cm and 20.1cm for the CoG and CoB in underwater configuration, with an estimated mass of $m = 924g$ and buoyant mass $m_b = 975g$, while in the flying configuration, the CoG is at 19.4 cm and AC at 20.4cm.

3.4.9 Mechanics

The BADAS is made mostly of carbon fiber material, as it's a very light weight, strong material, and easy to manufacture in a lab. Parts needed to connect components together are 3D printed

in PLA or ABS, as it allows to make faster iteration to get the components and assemble the drone.

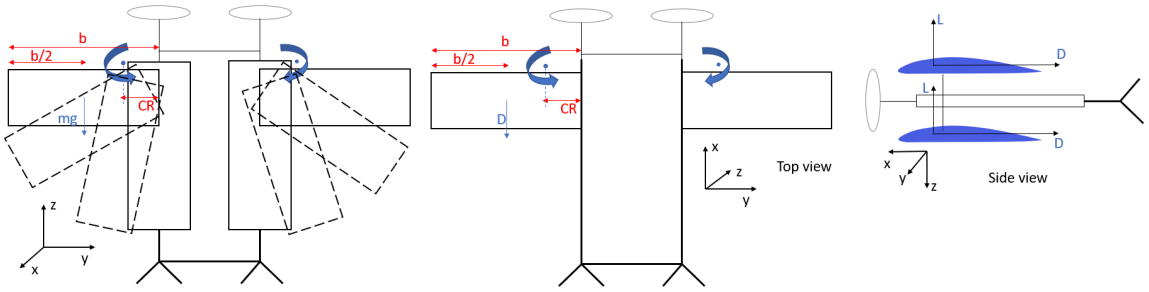
An important part of the mechanics of the drone is the wing-folding mechanism. At that scale, a power efficient and lightweight system should be used, as every added weight and power reduces the autonomy of the mission.

Based on the Figure 37, the design requirements are as follow:

1. Wing folding of 90 deg in less than 1 seconds. This is a reasonable timing for closing the wings when diving is initiating by closing the wings, making sure that the wings will be closed before crossing the water. A shorter time will be needed if the dive happens with open wings, as the time of free-fall is very short, as shown by Equation 13, and Figure 38.
2. In hover (Figure 37(a)), maximum torque of $2(b/2 - CR) \cdot m_w \cdot g$, to be able to open and close the 2 wings on each side while hovering.
3. In flight (Figure 37(b)), maximum torque of $0.5(b/2 - CR) \cdot D$, to sustain the drag on the wings.
4. Little to no power used in open or close position. This constraint is to ensure longer operation time, as most of the time, the BADAS will have the wings either open or close. Ensuring as little power consumption as possible at rest is essential.
5. Waterproof with little to no additional weight. As BADAS will go underwater quite often, this is a requirements as waterproofing moving components always comes with additional weight.

where:

b	=	span of one wing
CR	=	centre of rotation of the wing
m_w	=	mass of a wing
D	=	total drag on the drone when flying
$W_{arm} = b/2 - CR$	=	arm length for the wing



(a) Torque induced by weight while hovering

(b) Torque induced by drag while flying

Figure 37: Schematics for torque calculation on wing folding mechanism

$$\text{Height } z = h_0 + v_{0_z} t - 1/2gt^2 \tag{11}$$

$$\text{Impact when z=0 } 0 = h_0 - 1/2gt^2 \tag{12}$$

$$\text{Time to impact } t_f = \sqrt{2h/g} \tag{13}$$

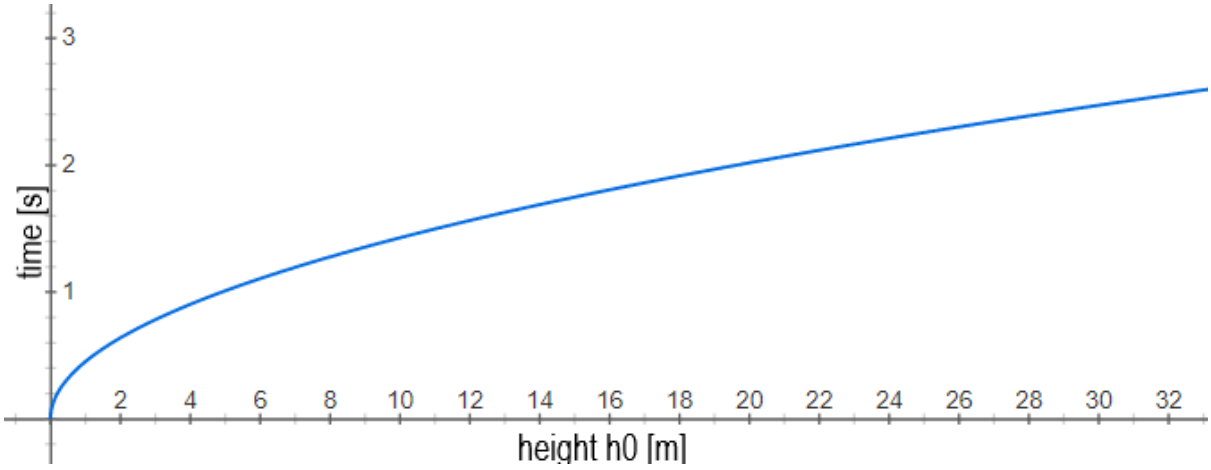


Figure 38: Diving time based on height

The focus was made on the last 2 constraints, as the first 3 can be solved by choosing motor and gear reducer that will satisfy the constraints. The last 2 however have to be solved by mechanical design.

The first step is to investigate the locking mechanism to avoid using much power in locked position. As summarized in detail in [114], this can be done using active or passive components, the first one adding additional electronics and control components to actively control when the locking happens, the second one relying on passive components, using gravity, friction, springs, or singularity in the mechanical system. We are inclined to use passive mechanisms as they require no energy while in locked mode and no external control.

[114] distinguishes the active and passive locking principle in mechanical, friction and singularities. The locking depends of the position of components and their direction of velocity for the 1st category, of the contact and engagement of friction surfaces for the 2nd, and of singular point of the mechanism that causes infinity transfer ratio in the last.

In the category of passive with friction, the overrunning clutch and non-backdrivable system are particularly interesting because of their small size and capability of being driven only by the input shaft to transmit a rotational motion. This is also the case for piezo lock and thermal lock [114], but those require an electric control to manage the expansion of the piezo or thermal component. Wormwheel is a way to transfer rotational motion around one axis to another axis by using a linear motion in between, which makes the system non-backdrivable by the output. However, the gear ratio in those system are extremely high, meaning that the speed of actuation is very slow. Clutch on the other hand have 1 to 1 gear ratio, simply transmitting the speed of the input to the output shaft in the same axis, but only work in a single direction because they depend on contact of friction surfaces based on the direction of motion.

3.4.9.1 Non-BackDrivable Mechanism

[115, 116] developed a new system similar to a clutch bearing, but by adding additional springs and rollers, they were able to drive the output shaft in both direction while the output shaft could not drive the input shaft at all. The Non-BackDrivable Mechanism (NBDM) that they created is based on the concept that while moving in one direction, the rollers that lock that direction first need to be unlocked and then the input shaft can drag the output shaft in 1-to-1 ratio by direct contact. The rollers for locking the opposite direction are kept close to their locking position using the springs, and as soon as the input shaft stops moving, the mechanism will self-lock thanks to the rollers.

As this system is self-locking (no external control needed), can be locked at any given position, and doesn't introduce a reduction of the speed, it would suit for the folding of the wings. Based

on their analysis and the flowchart to design the NBDM, a similar design was created and adapted with the intent to make it waterproof by design and directly mountable on the drone, for the BADAS and for the the SailMAV, which also requires a folding mechanism.

The main focus here is the torques that were to be sustained by the NBDM, as it would be used in direct transmission between the motor and the wing, in order to reduce the mechanical complexity of the system. To calculate these torques, the analysis is done using the schematic below for the drones, and the help of the design flowchart of [116], represented on the following Figure 39. Equations used for the derivation of the forces and torques are given by Equations 14 to 27 based on the parameters of the drones in Table 3.

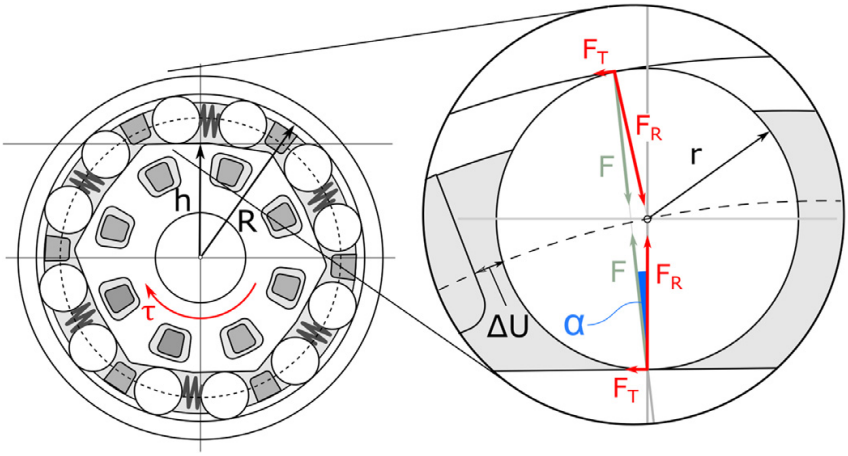


Figure 39: "Cross section of a bidirectional roller clutch. A torque τ applied from the output wedges half of the rollers between the cam and the ring, as long as the locking condition is ensured. Static interaction forces among the cam-roller-ring in the locked condition are displayed in the detailed view. Notation: α – contact angle; F – contact force; F_T – tangential component of the contact force, F_R – radial component of the contact force; ΔU – unlocking gap." [116]

Parameters name	Variable name	Units (SI)
wing length	W_l	m
wing mass	W_m	kg
wing arm length	W_{arm}	m
body width	B_w	m
total mass	m_T	kg

Table 3: Wing design parameters

While hovering:

$$\text{Force } Fh = W_m g \tag{14}$$
$$\text{Torque } Mh = W_m g W_{arm} \tag{15}$$

During flight:

$$\text{total Lift } L = W_m g \tag{16}$$
$$\text{total Drag } D = L/(C_l/C_D) \tag{17}$$
$$\text{Force } Ff = D/2 \tag{18}$$
$$\text{Torque } Mf = D/2W_{arm} \tag{19}$$

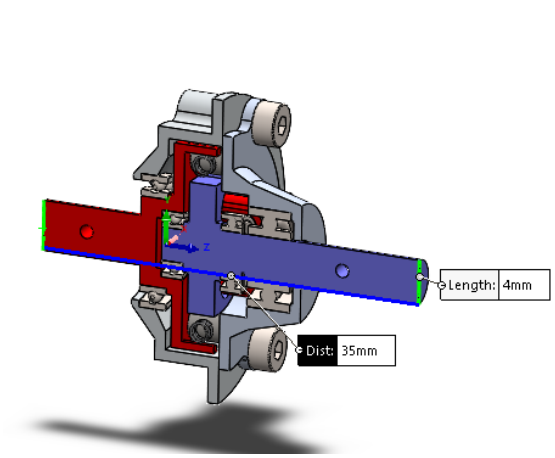
When holding the drone by the wing

$$\text{Reaction Force } Fr = m_T g \tag{20}$$
$$\text{Reaction Torque } Mr = m_T g(W_l + B_w/2) \tag{21}$$
$$\text{External Force } Fe = W_m g - Fr \tag{22}$$
$$\text{External Torque } Me = (FrW_l) - (W_m W_{arm} g) - Mr \tag{23}$$

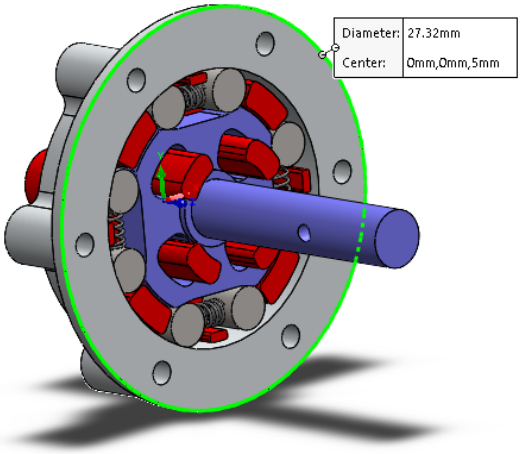
Internal forces on the NBDM components

$$\text{Tangent Force } f_t = 2 \cdot (\tau_{ext}/r)/(N/Fr) \tag{24}$$
$$\text{Radial Force } f_r = ft/\tan\alpha \tag{25}$$
$$\text{Unlocking Force } f_u = 2 \cdot fr \cdot (\mu s \cos\alpha - \sin\alpha) \tag{26}$$
$$\text{Unlocking Torque } \tau_u = f_u \cdot (N/2) \cdot (Fr - Rf) \tag{27}$$

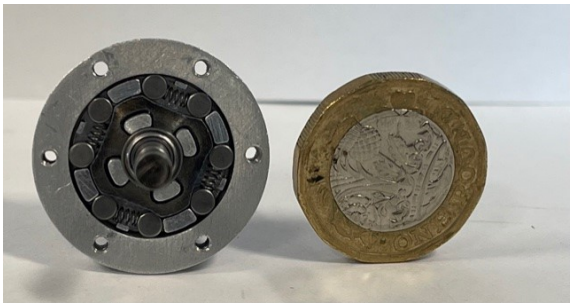
This led, after a few iteration of the design, to a manufactured version that was analysed and tested by Sandip Vijaykumar under my supervision [117], shown in Figure 40. The design was done in collaboration with André Farinha, another PhD student in the ARL and Dr. Zufferey, as the design would fit on another drone. The last few iterations were done solely by me, while Sandip Vijaykumar did the manufacturing and testing of the device.



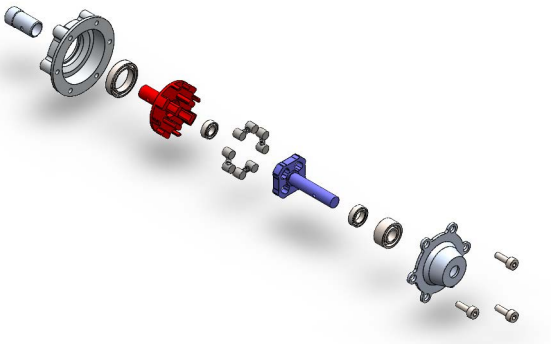
(a) Cut view of the NBDM inside parts



(b) Open view of the NBDM



(c) Open view of the assembled real size NBDM compared with a 1£ coin



(d) Exploded view of the NBDM with all its components

Figure 40: Different views on the NBDM device

3.4.9.2 Linear locking

However, as shown in the result of [117], the locking of the NBDM is not working as expected, and therefore this device could not be use for the BADAS yet. Another solution that was also used in other system is based on the 2-position locking mechanism used in landing-gear system for hobbyist airplanes. The system shown in Figure 41 was used also in SailMAV for the wings folding [28]. It used a linear motion transformed into rotational by pushing a lever with a special nut around a pivot axis, and the locking is done thanks to the shape of the lever and nut on both ends of the lever rotation.



Figure 41: Generic two wheeled shocking proof retract landing gear for 2KG RC airplane [118]

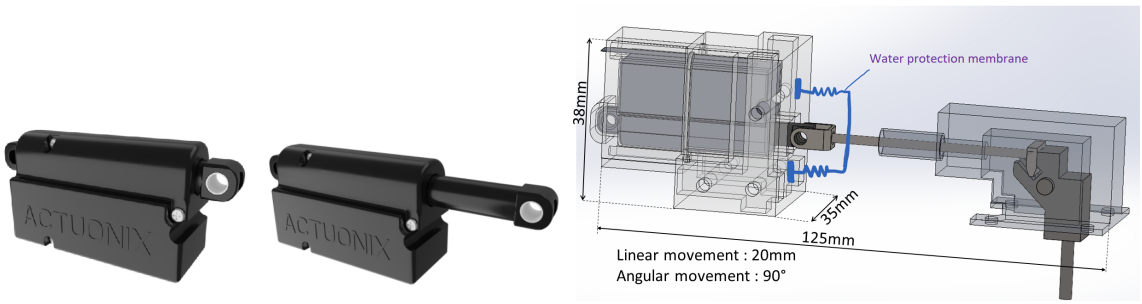
The nut is driven by a screw-nut system, so the motor turning the screw makes the nut move forward. The course of the nut is delimited by 2 micro-switches on each end of the trajectory of the nut, on which the nut bumps, closing the electric contact of the switch, providing a feedback to the motor controller that stops the movement of the nut. This was however quite complex to waterproof due to the mechanic around the pivot point. A modified version of this screw-nut was needed to have a better waterproofing capability.

A linear actuator working as a Pulse-Width Modulation (PWM) servo motor was used instead, with a fixed length of actuation. This motor actuator position is linearly dependant of the PWM signal that was provided as a control signal, making it easy to include in a design and in a control schema. The waterproofing can therefore be done towards the motor itself, around the linear movement of the actuator, as no other components are needed toward the rotation of the joint. This is done by using a plastic membrane, similarly to how bellows work, that fold and unfold around the linear motion. This is depicted in Figure 42.

3.4.10 Electronics and power consumption

The electronics of the drone is described here. Most components were chosen of the shelf to meet the required characteristics of the system. An overview of the system is shown in Figure 43.

The first choice for the electronic components is the Flight Controller Unit (FCU), as from this will depend the communication capabilities to other components. A mRo PixRacer R15 [119] is chosen, as it offers a compact form factor, 6 motor control outputs with OneShot/PWM support, FrSky telemetry port, and ESP8266 WiFi module which is going to be useful for wireless



(a) Actuonix PQ12 R linear actuator (b) Assembly for for folding

Figure 42: Actuonix PQ12 R motor

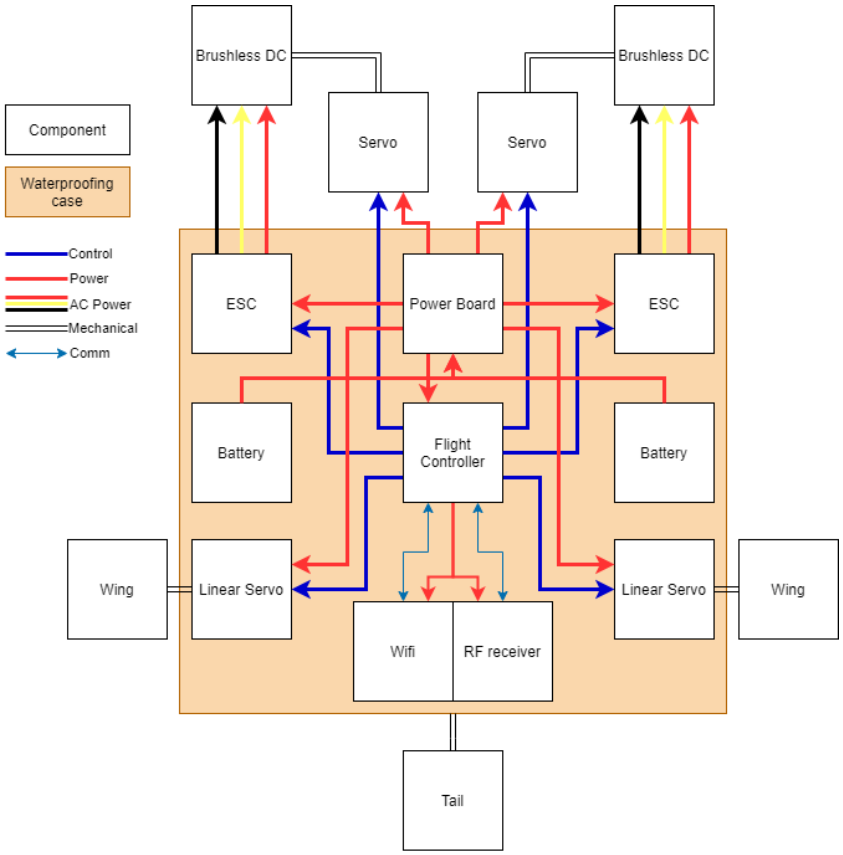


Figure 43: Schematics of the electronic components of the BADAS drone

component	brand	usage	percentage used	current [mA]	Voltage [V]	Power [W]	quantity	Total [W]
linear servo	PQ12-R	sparsly	5%	550	6	3.3	2	0.33
servo motor	TGY-50090W	in stall	80%	800	6	4.8	2	7.68
		idle	20%	20	6	0.12	2	0.048
brushless DC	iFlight Xing X2306 2750KV	hovering	10%	40000	16	640	2	128
		underwater/flying	90%	8000	16	128	2	230.4
								366.458

Table 4: Power budget

debugging and communication with the GCS. It is also well supported and documented in both PX4 [120] and ArduPilot [121] flight controller software and developer's community, which makes it a good choice for a FCU.

The communication using Radio Frequency (RF) with the Radio Controller (RC) is highly regulated in terms of frequencies that can be used, and commercial solutions let us choose from a standard 2.4GHz and a lower 900MHz, the second one having a longer transmission range. The R9M Lite transmitter and R9 MM-OTA receiver modules are 900MHz system that has "the ability to achieve long distances with one RF power output at 100mW" [122], with a power consumption on the drone of "100mA at 5V" [123].

The linear servo motor are chosen from the mechanical analysis in Section 3.4.9.2 to be the PQ12-R Micro Linear Servos from Actuonix, with a power consumption of 550mA at 6V. The servo motor used for the tiltrotor are chosen from a wide range of micro-servo motor, reduced to waterproof servo only, to be the TGY-50090W from Turnigy™, with metal gears, with a stalled current of 800mA at 6V and idle current of 20mA at 4.8 6V.

The brushless DC motors selected are iFlight Xing X2306 2750KV with 5050 propellers, having a maximum power consumption of 885W (50A at 16V) for a thrust of 1.6kg. They are driven by the ESCs VGOOD ARIA Slim 40A, limiting a bit the maximum power that the motor will be able to deliver, but allowing to control using the DShot protocol, which is faster than PWM control, adapting the speed of the motor faster.

To choose the batteries, the power budget needs to be evaluated and is shown in the Table 4. We can clearly see that the main energy consumption comes from the brushless motors generating the thrust for flying the drone when in hovering mode, then in airplane mode as well, reaching a total power of 640W and 128W respectively. By splitting the cost in 10% hovering and 90% flying, we reach a total energy needed of $\sim$ 366 Wh. Choosing 2 LiPo battery GNB 1800mAh 4S 130C, 219g, with continuous power of 3463.2W and total energy of 26.64Wh gives therefore a autonomy of $\sim$ 5 minutes.

The power distribution board can therefore be chosen to distribute power from the batteries of 14.4-16.8V to the 6V servo and linear servo, as well as 5V for the PixRacer, which can be done by the Matek FCHUB-W PDB 3-6S [124], a powerboard with a couple of voltage regulators within the correct power requirements.

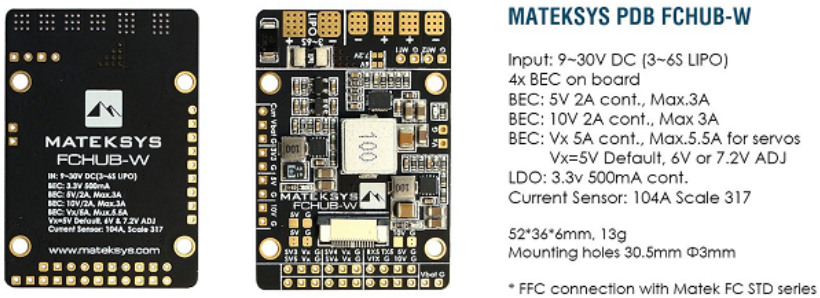


Figure 44: Matek FCHUB-W PDB [124]

3.5 Results and findings after manufacturing

3.5.1 Wing manufacturing

The wing design and manufacturing process was iterative to find the proper combination. Based on the original design ideas, the wings can be made out of plastic ribs, stronger spars and a plastic sheet for the skin.

The design suggests thin ribs of the shape of the airfoil, attached on the transverse spars. Due to the small size of the components, the ribs are slightly modified to have a part that is used as a spar between 2 ribs. This extension is also used to make a structure that will hold the shape of the skin in between the ribs. This is needed as the plastic sheet will be unable to sustain itself as very flexible.

The spars are chosen to be carbon fiber tubes, lightweight and strong, as well as 2 stainless steel rods, to add some resilience to the brittleness of the carbon fiber. The bigger spars will be in carbon fiber, while the steel rod will be as small as possible.

The plastic sheet used is made from PolyVinyl Chloride (PVC) in a layflat tube format, with a perimeter slightly bigger than the airfoil length. This allows to cover the whole wing, and by heating it, shrinking the PVC sheet, sticking on the wing. The PVC has a Glass Transition temperature (Tg) in the range of 80-90°C, so the plastic for the ribs need to have a Tg higher than this. Some more Tg are shown in Figure 45 for some different polymers.

For fast prototyping of complex 3D object of small scale, 3D printing is currently the best option. Fused Deposition Modeling (FDM), also called Fused Filament Fabrication (FFF), is the most common method for 3D printing, extruding filament of thermoplastic by heating it, stacking layers of melted plastic on each other in order to fabricate the part. This method works with a set of thermoplastics, including Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), PolyEthylene Terephthalate (PET), Glycol modified version of PET (PETG), PolyCarbonate (PC), high performance polymers (such as PEEK), or PolyPropylene (PP) [125].

Amongst those, ABS has a Tg of 104°C, above the Tg of the PVC. The parts where therefore printed in ABS . The individual ribs were hold together with the spars of carbon fiber and of steel, then wrapped in the plastic sheet, and put in an oven at 85°C, to make the PVC shrink on the wing. A few of tries were needed to get the proper duration in the oven. Indeed a long time would mean more shrinking of the PVC tube around the wing, making wrinkle where it was not supported by the structure.

Here are some pictures of the resulting wings in Figure 46.

3.5.2 Wing water emptying speed

As the wings were manufactured, a test could be implemented to capture the speed of emptying the water from the wing while doing a hover take-off with the wings folded. Indeed, this is going to be the take-off method from the water body for the drone, and we would like to wait as little as possible to open the wings in order to transition to forward flight. As water is in the wings while underwater, we need to wait some time until the water exits the hollow wings, so that the drone doesn't carry extra weight.

This test was done in a condition similar to actual takeoff, but with a single wing carried out of the water by hand. The water is seen to leave the wing progressively without staying stuck on the wings ribs. It can be seen on the Figure 47 that it takes between 300 and 370 milliseconds to lift the wing out of the water, and 1000 milliseconds for 90% of the water to leave the wing. Based on this simple test, we can assume that the wing can be functionally used in the water.

In figure 47(j), we see that water is still dripping from the wing, but very slowly. This is mainly due to water capillarity on the skin and ribs of the wing. We can assume that this will be a relatively small amount of water compared to the initial volume that filled the wing.

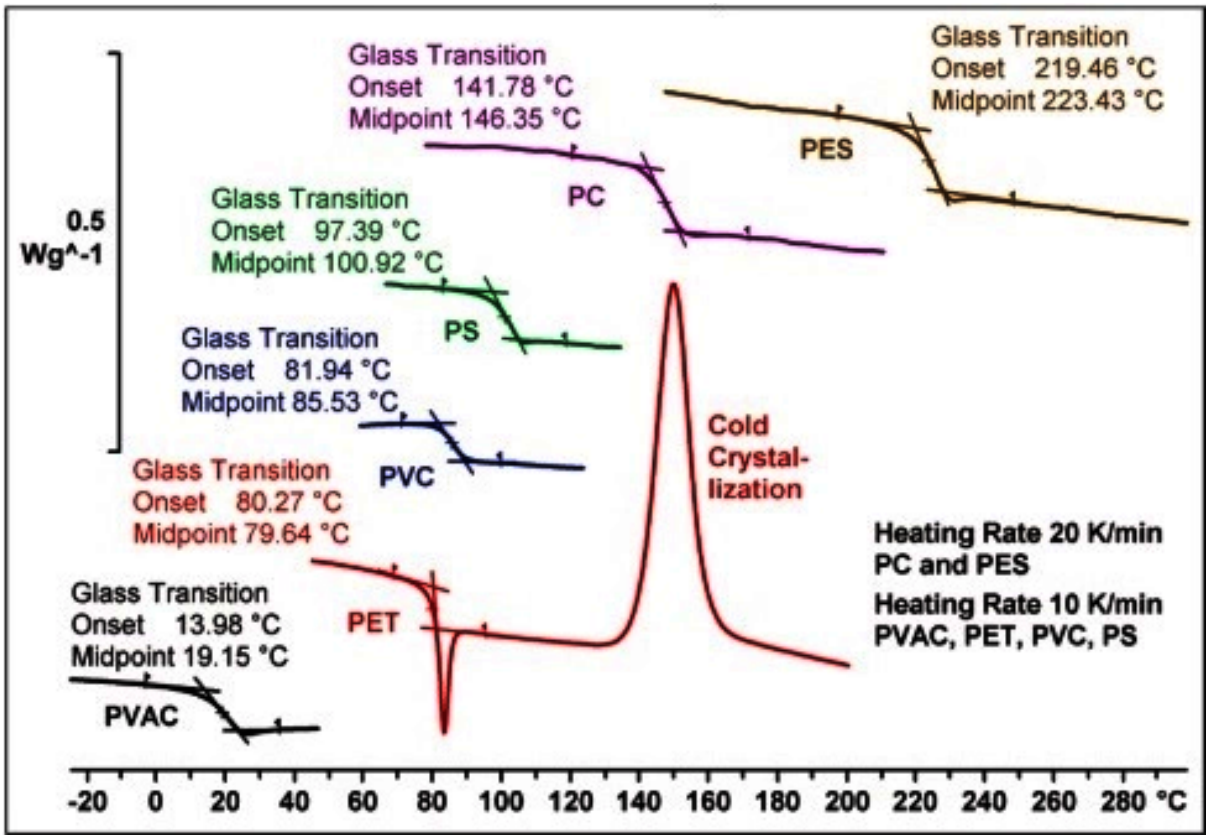
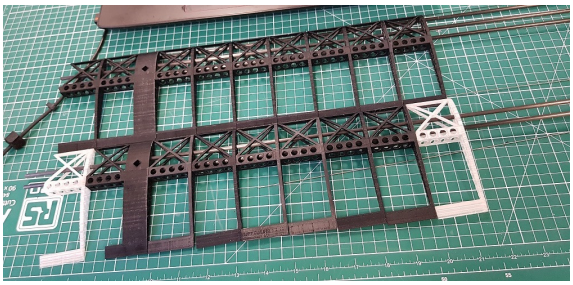
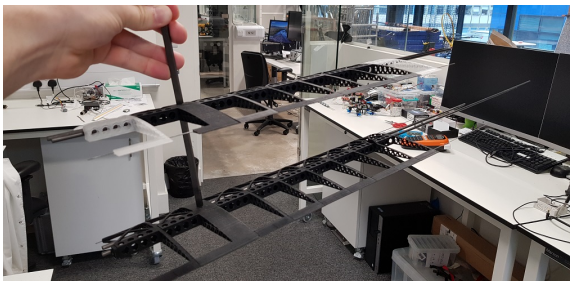


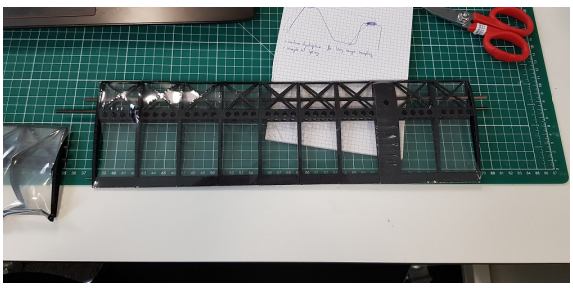
Figure 45: Glass transition temperature measurements of different polymers using DSC [126]



(a) Wing assembly before the skin is added



(b) Biplane wings pre-skin assembled

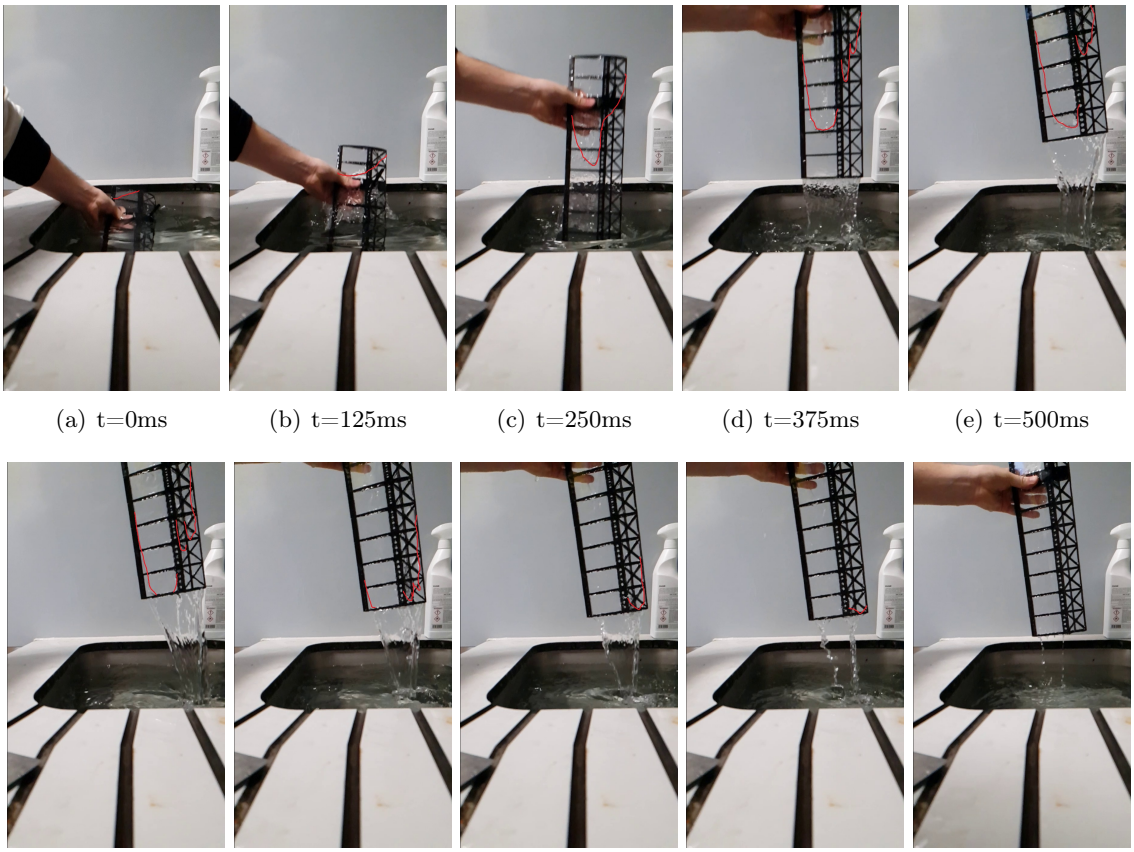


(c) Good assembly of the wing with the skin



(d) Broken wing where the skin sheet twisted the underlying ribs during the heat shrinking process

Figure 46: Wing assembly



(a) t=0ms (b) t=125ms (c) t=250ms (d) t=375ms (e) t=500ms

(f) t=625ms (g) t=750ms (h) t=875ms (i) t=1000ms (j) t=2230ms

Figure 47: Water emptying from wing test

3.5.3 Hovering flight

The first step for showing the flight capabilities of the BADAS is the hovering flight. This is done by manually tuning the PID control gains of the multicopter mode of the ArduPilot software. The first tests were done with the drone hanging on ropes to avoid crashing it and breaking multiple times.

The PID tuning is done following the the Ziegler–Nichols method, which first set the I (K_I) and D (K_D) gain to 0, and increase the P gain (K_P) unstable the system starts to be unstable and to oscillate, at which point the K_P is recorded as K_{MAX}, and the frequency of oscillation f_0. The K_P is then set to $0.6K_P$, K_I to $2f_0$ and K_D to $0.125/f_0$ [127].

Other methods than Ziegler-Nichols exist, such as Cohen-Coon or Chien, Hrones and Reswick, both open-loop techniques, or Tyreus-Luyben in closed-loop [128]. It is shown that Ziegler-Nichols gives a very good starting point to tune the parameters, by providing better disturbance rejection in the model. This is favorable as the system is very dynamic and sustain a lot of disturbance early stages.

Those gains where first looked for the pitch with no roll nor yaw control, then pitch and roll, and finally the 3 together. Indeed, it was noticed that the roll and yaw control had a big influence on the pitch behavior, and tuning the 3 DoF at the same time was not easily feasible.

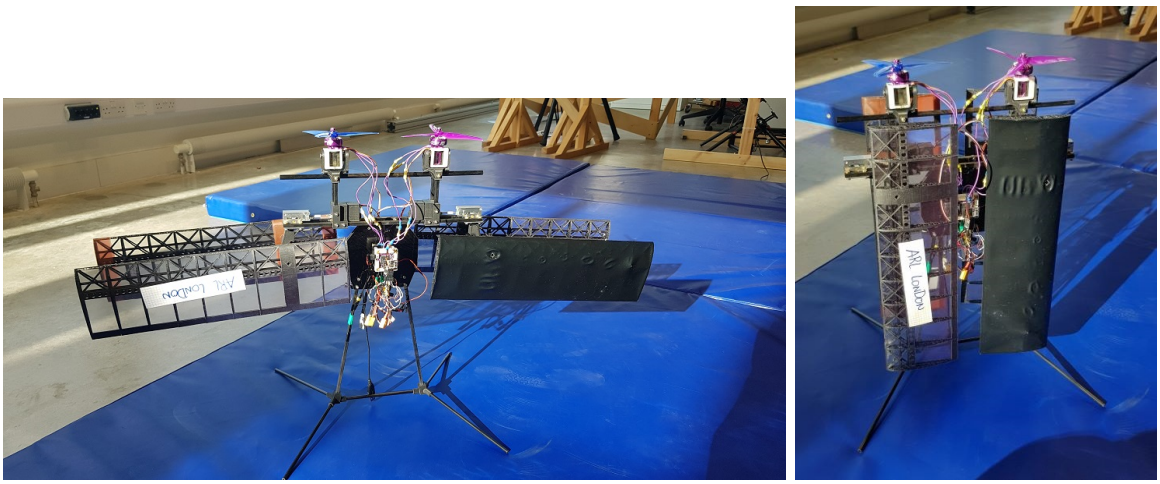
Once manual tuning was done, computer aided tuning was able to run as the BADAS could do some small flight without crashing, recording enough data to run PID-analysers like the PX4 flight review analysis.

This resulted in BADAS being to hover for the whole duration of its battery lifetime, which lasted 3 minutes. This can therefore correspond to 15 minutes of airplane-mode flight.

3.5.4 Wing folding mechanism

The wings folding, opening and closing mechanism was an important part of this project, that can be tested relatively easily even when the drone is not flying. More tests will need to be done when the BADAS is able to hover and fly as an airplane properly.

This static test requires to assemble the biplane wings on the folding mechanism based on the linear servo motor and the modified landing gear system, and try to open and close the wings. The results can be seen in the Figures 48.



(a) BADAS assembled with open wings

(b) BADAS assembled with closed wings

Figure 48: BADAS open and closed wings

3.5.5 BADAS, complete assembly

Finally the entire drone was assembled and was ready for more tests and future development. We can see here the 3D model and the actual drone.

3.6 Discussion

A lot of inspiration was taken from previous iterations with the main purpose to develop a multi-modal platform for a long-term project. At the end of the project, we can see a fully manufactured system, with capabilities as per the specifications of the section 3.1.

The BADAS can indeed take-off and land vertically, transition to an airplane flight mode to increase its endurance and flight range, and fold its wings for diving in the water, efficiently saving energy from its flight altitude to underwater depth. It can then navigate underwater as a submarine, and take-off gradually from the water surface, with wings folded, getting ready for another flight.

Neither flying as an airplane nor the underwater part have been tested during this project due to the COVID situation. Each of the steps can be demonstrated individually, but not end-to-end in one single flight.

3.7 Future work

As this project was supposed to span over 4 years and not 2, the platform was thought out with a long-term purpose, and was not entirely tested at the time of writing. Here are some of the future work topics that would have been addressed in the close future of the project:

3.7.1 Lift and drag coefficient

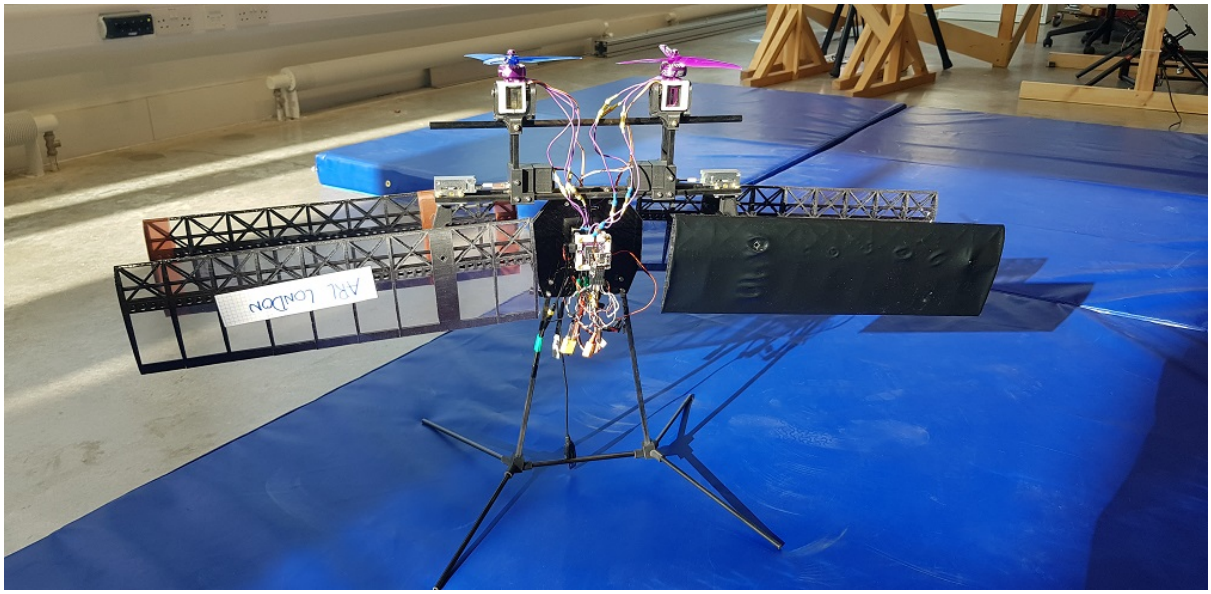
The aerodynamic properties of the entire BADAS need to be characterized. The first thing to make sure the biplane configuration is good enough for the BADAS drone and is actually a good solution, the second is to characterise the lift and drag while the drone is folding its wings and transitioning between airplane mode and hover or diving. Indeed the forward transition (from hover to airplane) and backward (airplane to hover) are highly dependent on the stalling of the wings and the control can vary a lot based on that. The aerodynamics properties would need to be known with according to 3 parameters to be used in a live control of the BADAS: the speed of the wind [0 to 30m/s], the folding angle of the wings [0 to 90°], and the angle of attack of the drone [-20° to 110°]. The angle of attack range is much bigger than usual because of the transition from airplane to hover, inducing a 90° rotation which impact the flow of air around the aircraft.

3.7.2 Flight control

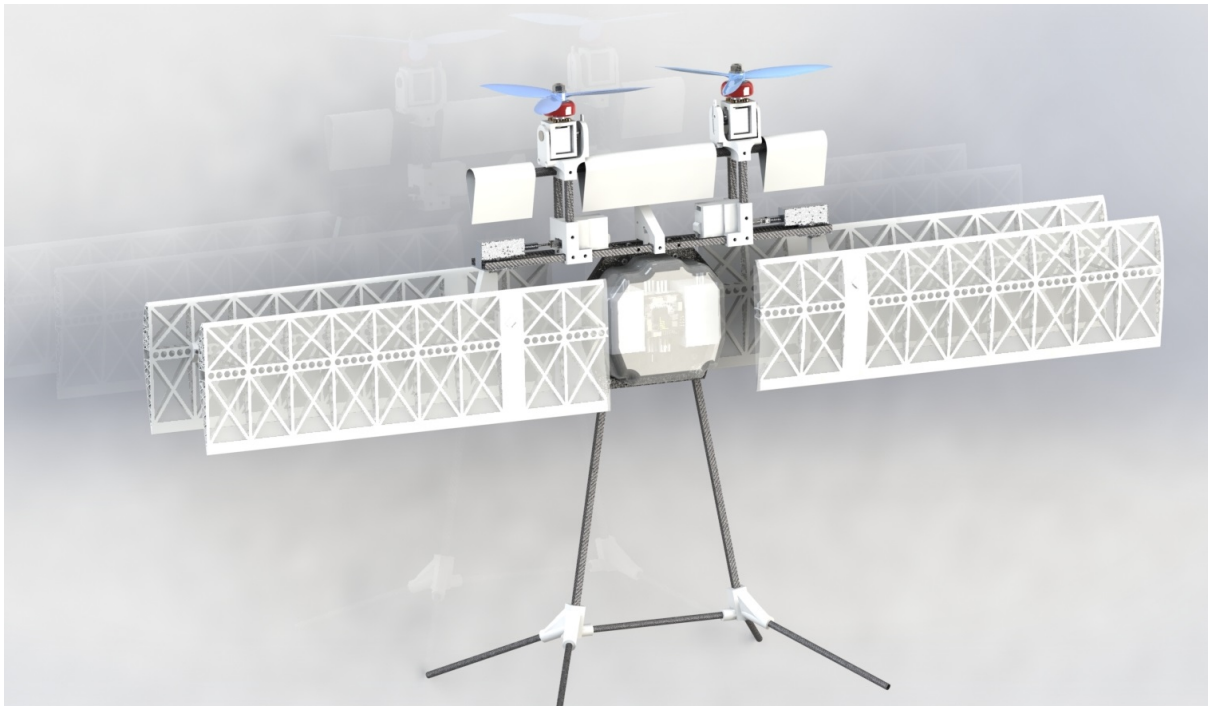
The flight control was until now based on existing autopilot control software to make the BADAS a fast prototype of the platform. However, the transition between hover and airplane mode back and forth are still in development in the scientific community and not optimal, the platform design having an important impact on the control laws. An important work can be done in this direction with the BADAS platform.

Another control that has to be implemented and researched is the diving control. As seen in the first AquaMAV, no control was able to prevent the drone to start spin-rolling on dive when the wings were getting closed. With this platform, the control can be kept longer and the diving trajectory could be optimized by proper control. A method that keeps the wings open as long as possible by tracking the right moment to close them (such as optic flow) could be investigated.

The water take-off is also something that was giving interest while developing the project. Indeed, being a gradual take-off method, the long transition from the water to the air will be



(a) BADAS assembled



(b) CAD model

Figure 49: Assembled vs CAD model of the BADAS

dependent on the sea-state, which can cause a lot of disturbances on the drone. Having a control system that can withstand the waves while taking-off has not been shown for a slow take-off drone.

Another control schema could be investigated to improve flying after a incident causing a loss of a wing. Usually, losing a wing is catastrophic for an airplane, resulting in a crash in most cases. The design with the tiltrotors in front could in theory sustain a wing-loss and still be able to fly, as the thrust could compensate the roll induced by the remaining. A design with a wing that can be folded gradually would allow to progressively reduce the lift of one side of the drone until the system cannot compensate anymore. This control law could be developed and analysed in simulation and then tested on practice. This would be a critical safety measure for drones diving in water, as damage can arise easily on those systems.

3.7.3 Underwater navigation

In the scope of this project, the underwater topics were thought, researched and design but not tested. This would be a important part of the future work on this platform to show a proper full cycle of a mission. With the bicopter tiltrotors capability, the control scheme should be fairly similar to either hovering or airplane-mode flying, but with a denser medium, lower speed and the buoyancy force providing most of the needed "lift". The torque induced by the buoyancy centre should be checked, and the water take-off part is also something that has not been tested and could be investigated.

3.7.4 Water sampling system

While this drone was developed with the intent to be used for water sampling, no such system has been put on the drone itself. It can therefore be further researched and added to the platform accompanied by the required modification to fit it. This can be developed separately from the platform itself until the water sampling system is working and tested, then adapting it to the BADAS or its future version.

3.7.5 Design improvement

The design itself can always be improved, and in the case of the BADAS, one of the main design flaw would be his shape on water entry. Even when developed knowing from the start that a slender shape was needed for a proper entry, the dual propellers in the front make the drone shape not quite proper for fast entry in water. A change of design would however be needed for a better shape, which would require a lot of rework on the drone itself. One possible solution would be to use propulsion tiltrotors on a delta-wing aircraft, whose front shape is more suited for water entry without wing folding needed. The takeoff from water can be done in a similar way as for the BADAS but pulling the drone out of the water in the reverse direction, and transitioning to flight using in flight propeller speed inversion. This can be done more easily these days with the new ESC firmware, allowing the motor to abruptly reverse its rotation direction, propelling instead of pulling.

4 Conclusion

This project was a research and exploration of a novel multi-modal drone capable of navigation freely in air and in water, including the transitions between the two media. Based on existing platforms, the development of the BADAS used a number of combination from different domains of engineering in order to assemble one robotic platform capable of more than the sum of its individual components. The main challenges were actually the integration between different domains to reconcile 2 fluids which differ mostly on their density, making it hard to construct a single drone compatible with both.

We saw the exploration of the different configurations of airframes, and chose from those the one that would best suite the underwater requirements. A bicopter tailsitter configuration, with tiltrotors and no physical tail, was chosen for the airframe, while the folding wings mechanism was implemented to allow a fast transition from air to water. Hollow wings were developed and manufactured in the college workshop at a small scale to provide neutral buoyancy for the drone, allowing it to rely only on the trust generated by the propellers to navigate underwater as well, without needing an extra buoyancy system, which would have added more weight. The take-off from the ground or from the water can be done in a seamless way with the wings closed thanks to the vertical take-off and landing capability that the tailsitter offers, while flying long range can also be achieved by unfolding the wings and morphing the BADAS into a proper tail-less biplane, generating enough lift to fly at low speed.

The mechanical assembly of the drone integrates relevant electronic components, chosen to be easily adaptable and changed later on if needed. The brushless DC motors controlled with the individual ESCs are generating the trust needed to fly and hover, while the PixRacer FCU and running the open-source firmware from Ardupilot controls the attitude and relays the remote control input from the pilot with the long range antenna at 900MHz. The 2 LiPo batteries are powering the whole system at $\sim$ 16V for about 4 min of hovering and 15 min of flight, and through the Mateksys PDB, redistributes the power to the 5V servo motors used in the tiltrotor and the 6V linear servo motors for the folding wings mechanism.

A specific self-locking mechanism, the NBDM is investigated and researched to provide a continuous locking position that would allow the sweep angle to be controlled smoothly, providing 2 more Degree of Freedoms for the robot, which would improve for free upon the limited 4 DoFs that were initially chosen. This would increase the capabilities of the BADAS even more, by having a 2^{nd} roll control. The NBDM was however not working at the end of the project and a backup solution using the linear servo motor and the landing gear 2-positions locking was used instead.

While there is still work to do for this project to be fully functional, this thesis put the ground basis for the multimodal platform that would eventually be able to complete a full cycle of the air-underwater-air locomotion.

Signature

London, June 9, 2024

DI TRIA Julien

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