An Open-Source Watertight Unmanned Aerial Vehicle for Water Quality Monitoring

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***Abstract*—This paper presents an open-source watertight multirotor Unmanned Aerial Vehicle (UAV) capable of vertical take-off and landing on both solid terrain and water for environmental monitoring. The UAV's propulsion system has been designed so as to also enable the active control of the UAV's drift along the water surface. This low power locomotion method, novel to such a vehicle, aims to extend the available operation time on water bodies' surveys. The ability to take-off from water allows the UAV to overcome any obstruction that appears on its path, such as a dam. A set of field trials show the UAV's water-tightness, its take-off and landing capabilities in both land and water, and also the ability to actively control its on-surface drifting.**

I. Introduction

Current techniques for water monitoring rely on manned teams [1], on remote information, such as the one provided by satellites [2], [3], or on the deployment of Unmanned Surface Vehicles (USV) [4], [5], [6], [7]. The remoteness, and vastness of water bodies render the use of manned teams expensive and dangerous. Remote sensing offers an alternative but the data gets too often outdated, a fact that, added to its inadequacy to retrieve samples, significantly limits its applicability. Conversely, a USV allows long-lasting monitoring of remote and vast water environments and also to retrieve water samples.

Despite relevant for environmental monitoring of water bodies, there are many scenarios to which the use of a USV is rather limited. For instance, the operation of such vehicles on open sea may be severely compromised in face of powerful waves and strong tides. Such harsh conditions can damage sensory equipment or even the vehicles' overall structure. On coastal regions, the risks are more related to the shore's proximity, which induces turbulent waters and potentially reveal sharp-edged rocks. Sparsely distributed water bodies, either near the shore or inland (e.g., groups of small lakes or puddles), posit a different challenge. Gathering data using a USV in these regions is logistically cumbersome as it requires human intervention to carry the vehicle over land, rendering the approach impractical. The same difficulties arise when navigating to hard-to-reach locations due to the presence of obstacles along the water bodies' courses, such as dams, rapids, waterfalls, wave breakers, and debris (see Fig. 2). A putative solution to this problem, yet to be addressed, is the use of amphibious vehicles that could autonomously navigate on land so as to reach the next water body's segment. Although amphibious robots are already available [8], [9], the ability to move them autonomously on unpredictable and unknown ground is still an open problem. If such a vehicle would have to overcome man-made structures, such as a dam, would most probably require human intervention. Moreover, such an operation would be excessively consuming in both time and energy.

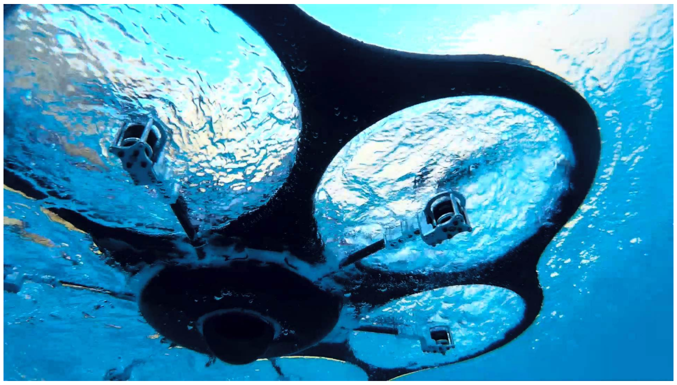

Fig. 1. The proposed UAV prototype taking-off from the water surface.

Waterways exploration using aerial vehicles has also been subject of interest in recent years with efforts made for autonomous river exploration [10]. For in-situ water quality monitoring and sampling, rotary wing solutions [11], [12] have also been proposed. In addition to be able to perform in-situ water sampling and retrieval, a watertight aerial vehicle can always opt for the safest medium, either water, air, or land in case of an emergency (e.g., strong currents, rotor failure, strong winds).

An Unmanned Aerial Vehicle (UAV) performing environmental monitoring needs to be able to search for a suitable landing site once its mission is concluded. This is a challenging problem as potential dry landing areas on riverine environments are often either occluded by dense vegetation, such as tree canopy or low-hanging branches, or very difficult to distinguish from unreliable terrain on marshes and mudflats. Large waterways present a different challenge, namely, the lack of nearby landing areas, which requires a larger energetic autonomy from the aerial vehicle or a limited operation range.

An alternative to landing on dry ground is to allow the aerial vehicle to land on an autonomous surface vehicle also engaged

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(a) (b)

Fig. 2. Two typical obstacles that a versatile autonomous vehicle should be able to tackle when performing environmental monitoring on water bodies. (a) A rapid in a riverine environment. (b) A wave breaker.

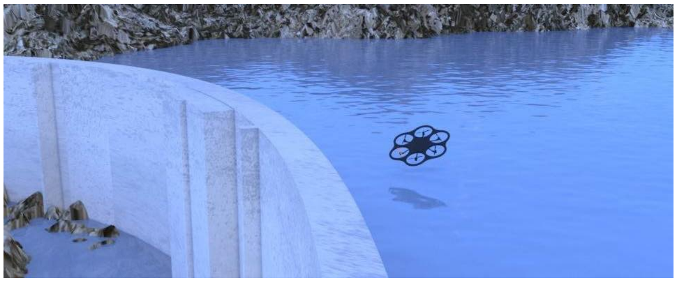

Fig. 3. A 3-D rendering of the proposed watertight UAV overcoming a dam towards the next water sampling waypoint, which would be unreachable for water surface vehicles.

on the monitoring mission [6]. However, as already pointed out, relying on a USV may be limited in several scenarios. To relieve the UAV from this constant dependency, it needs to be able to land on the water surface itself. Bearing this in mind, this paper proposes an open-source[1] autonomous and watertight UAV with Vertical Take-Off & Landing (VTOL) capabilities on both land and water (see Fig. 1). The proposed UAV's propulsion system has been designed to also allow the active control of the UAV's drift along the water surface. This low power and novel locomotion method aims at enabling long lasting water bodies' surveys. In a sense, the UAV performs as a surface vehicle until an obstruction appears along its path. The obstruction is then overcome by the UAV by means of a take-off-flyby-landing sequence (see Fig. 3).

There are a few parallel developments on commercial remotely controlled VTOL vehicles capable of landing on water surfaces (refer to [13] for a recent survey). Differently from these parallel developments, the workload of the VTOL herein presented includes enough computational and sensory power to enable autonomous behaviour. In fact, it is fully compliant with the Robot Operating System (ROS) [14], which is the current *de facto* standard in the robotics community. As a result, the VTOL is easily integrated in larger robotic teams and can also be easily extended with novel and advanced navigation and perception modules. Furthermore, the commercial nature of the parallel developments result in a closed design and absence of published systematic field trials. In addition to open the design to the community, we also report uncommon behaviours for a watertight VTOL, such as controlled drifting on the water surface and low altitude flight exploiting the ground effect. Finally, we provide the first specification of how long-lasting environmental monitoring surveys in segmented water bodies could exploit the benefits of watertight VTOL.

This paper is organised as follows. Section II describes the system's design. Then, in Section III, the navigation and control systems are presented. The results obtained in a set of field trials are summarized in Section IV. Finally, some conclusions and future work avenues are drawn in Section V.

II. SYSTEM DESIGN

A. Structure Design

The watertight system's main purpose is in-situ water monitoring and, for that, it needs to fulfil a set of functional requirements. The robot should be able to take-off and land on solid ground as well as on water surfaces, while carrying a dedicated sensory payload for water sampling.

Fixed-wing aircraft have significantly more payload capabilities and energetic autonomy than rotary-wing vehicles. However, the extensive landing areas required by fixed-wing aircraft render a rotary-wing configuration with vertical take-off and landing capabilities better suited for the task at hand. To increase the UAV's maximum payload with an additional redundancy-based fault tolerance, a six rotor configuration was chosen. This is key to ensure that the aerial vehicle is able to keep flying towards a safe landing site whenever required.

The major concern of using a UAV in a water environment is the vehicle's ability to sustain itself in the water surface. This demands for a watertight vehicle with enough buoyancy as to avoid damaging its control and propulsion systems. To ensure these properties, the vehicle core is made of carbon fibre with a high strength-to-weight ratio and low density core filling. The UAV's centre of buoyancy was designed so that while the vehicle rests/floats on the water the propellers remain above its surface, easing considerably any take-off procedure. In addition to buoyancy, the UAV needs to be robust against collisions with vegetation, other small obstacles, and the water surface itself. This constraint is met with an enclosed propeller design (see Fig. 1). An additional feature available on the UAV is the ability to use its propellers' thrust to cruise along the water surface, using less energy than it would by flying. This novel locomotion method allows the vehicle to exploit existing water currents to expand its operational capacity following river-streams and leapfrogging obstacles. While being pulled by water currents, the vehicle needs only to perform small motion adjustments through the same propulsion system it uses to fly.

An important factor in real life monitoring campaigns is to ensure ease of use and maintenance. This includes a straightforward exchange of batteries and damaged electronic components. To do so, an easily removable single central cover was designed which relied on a screw-on top with an non-adhesive sealant material between the cover and the UAV's frame. From the sealants tested, namely, silicone strips, rubber

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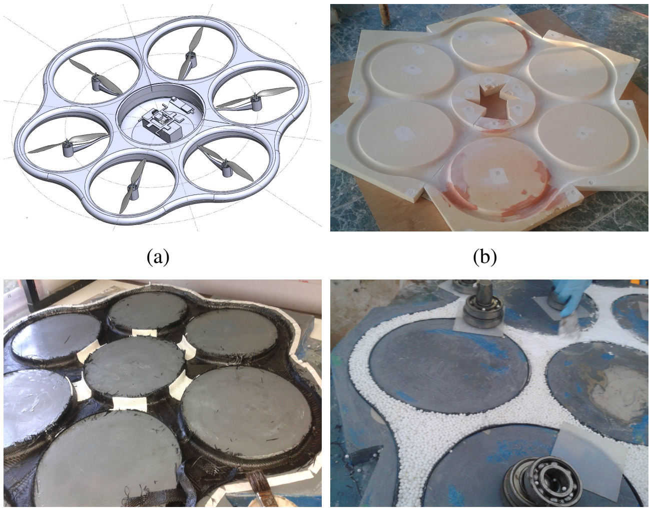
[1] Construction diagrams, source code, and videos can be downloaded at the RIVERWATCH experiment site: http://riverwatchws.cloudapp.net/.



(a) (b) (c) (d)

Fig. 4. The UAV design process. (a) The structure design in SolidWorks. (b) The negative mold machined on a CNC. (c) The carbon sheet applied over the mold. (d) The filling with microspheres

strips, and neoprene strips, the latter achieved the best results. When compressed tightly together, the neoprene strips ensured watertightness.

During the design and construction phases, a 3-D model of the UAV was designed and validated with stress tests in SolidWorks. This design was later used to create a negative mold for the symmetrical top and bottom halves made of CNC milled Polyurethane high density foam. The mold was then reinforced with several layers of microspheres and epoxy resin and highly polished. The bottom and top halves were made individually with a low weight ($90\,\mathrm{g/m^2}$) carbon fibre that was vacuum molded, and cured at ambient temperature. To achieve the strongest and lightest structure possible, each part was filled with an innovative mixture of small spheres of polystyrene with Glass Bubbles (Microspheres) and epoxy resin. These allow the structure to resist the stress of successive landing, take-off, and immersion procedures. Finally the two parts were joined using carbon fibre tape impregnated with epoxy (see Fig. 4).

B. Hardware Architecture

The UAV's propulsion is provided by six Altigator A3536 motors equipped with 13 inches diameter and 4.5 inches pitch carbon propellers, each capable of providing 2 kg of thrust. The ESCs (Electronic Speed Controllers) adopted were the high efficient 30A Afro ESCs with a firmware capable of 1 kHz refresh rate. For energy supply, a single MaxAmps 12000 mAh XL 4s 120C LiPo battery or two 11000 mAh 4s 40C LiPo batteries provide between 15 minutes to 25 minutes of flight time, depending on the chosen battery configuration.

To support the low-level control system and high level functionality, the UAV uses a modular architecture (see Fig. 7). Low-level and high-level boards are separated ensuring that the basic control is decoupled from functions supporting autonomous behaviour. The UAV is equipped with a VRBrain from Virtual Robotix for low-level control, which uses a Global Position System (GPS) device from Ublox, an onboard Inertial Measurement Unit (IMU) based on MPU6500 and a MS5611 barometer for pose estimation. This low-level board is connected to an Odroid-XU from Hardkernell, which provides high-level processing capabilities, equipped with an Exynos Octa-core CPU running the Indigo distribution of Robot Operating System (ROS) [14], over a lightweight Linux distribution, namely the Xubuntu 14.04.

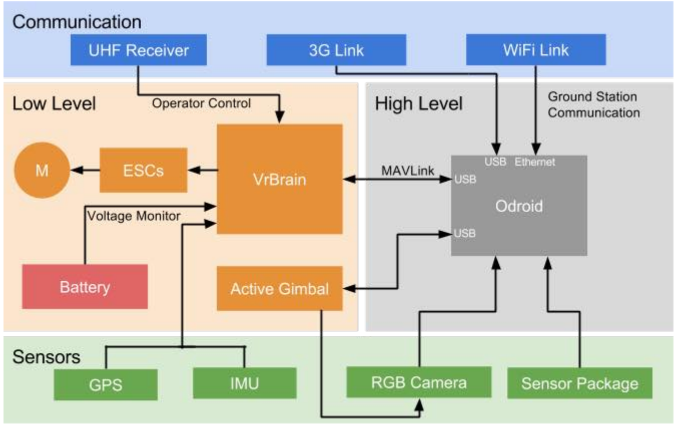


Fig. 5. Hardware System Architecture overview.

(a) (b)

Fig. 6. Video acquisition system. (a) Gimbal placed inside the UAV structure with a plastic dome. (b) Underwater images retrieved using the UAV's monocular camera.

Perception is ensured by a downwards-facing RGB monocular camera, placed on an active gimbal. The system is protected inside a plastic dome for an unobstructed 150 degree view (see Fig. 6). Then, once the UAV floats on the water surface, and the dome becomes completely submerged, underwater images may now be captured.

III. NAVIGATION AND CONTROL

The software architecture was envisioned to improve the UAV's robustness in harsh environments by decoupling high-level and low-level functionalities (see Fig. 7). This allows the UAV to revert to essential functionalities when it needs to save energy. This fallback is especially relevant in remote environments, where the UAV will need to keep his energy expenditure to a minimum. In this section an overview of the selected architecture is laid out.

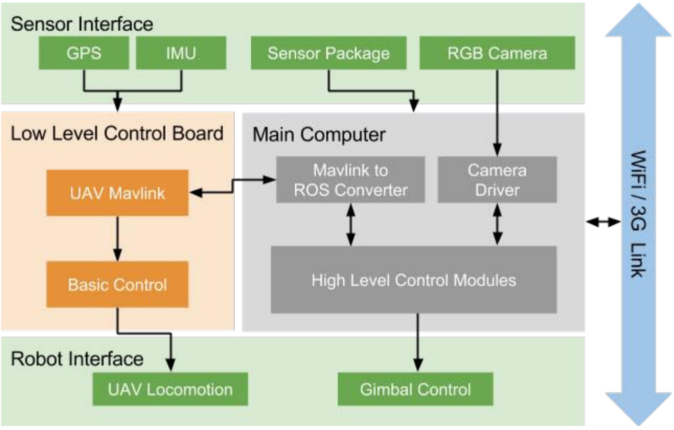


Fig. 7. Software System Architecture overview.

The low-level control and basic navigation functions are supported by a customized open source platform, the Arducopter. This framework encompasses a flight controller with features that range from autonomous take-off, landing, and waypoint following. The communication between the low level flight controller and higher level processing unit is established through MAVLink, which is a lightweight protocol designed for aerial vehicles. A dedicated software module abstracts the MAVLink protocol to comply with the Robot Operating System (ROS) framework [14]. This allows seamless data exchange between the flight controller and the higher level navigation ROS-based modules.

The sampling process is executed following a line-sweep pattern around the area the operator defines upon the UAV's aerial imagery. The UAV is then assigned with a given survey, involving one or several water bodies, to which it plans accordingly the most suitable path and mode of locomotion. While approaching a water body, the UAV flies to the designated initial waypoint and lands on it once it is reached. There, the UAV changes its locomotion method so as to cruise on the water surface through the several subsequent waypoints. While cruising, the UAV stores a dense data stream from its on-board payload sensors. Whenever a portion of land, or any other obstruction (e.g., a dam), separates the UAV from its next waypoint, the UAV takes-off the water surface to fly over the obstacle, and eventually land again on the next sampling point.

IV. FIELD TESTS

To validate the developed UAV, a set of experiments were performed. The first experiment was carried out on a controlled environment, namely, a swimming pool. Then, a few field trials were run in a real world $85.000\,\mathrm{m}^2$ water body.

A. Pool Tests

The objective of this first set of experiments was to assess the UAV's design appropriateness to a water environment. The trials began by checking the vehicle's watertightness by submerging it at several depths, followed by buoyancy and rotational stability tests. Next, the platform was subjected to drop tests from different heights to check if it could survive a crash on the water surface without getting its inner components damaged. Finally, take-off, landing, and on-surface locomotion tests were conducted.


(a)
(b)

Fig. 8. Preliminary validation in a swimming pool. (a) The UAV fully submerged. (b) The UAV hovering above the water surface.

To check its watertightness, the vehicle was submerged for five minutes at depths $0.0\,\mathrm{m}$ (fully submerged), $0.2\,\mathrm{m}$, $0.6\,\mathrm{m}$, and $1.0\,\mathrm{m}$ (see Fig. 8(a)). Although it is not expected the UAV to be subjected to such extreme depths in real life applications, the robust operation under these circumstances assures the vehicle's watertightness.

The UAV also has to be able to keep floating on the water surface. Bearing this in mind, buoyancy tests were performed by loading the UAV with weights up to the double of its normal operating payload of $1800\,\mathrm{g}$. The relationship between the buoyancy and gravity centres affects the stability of a vessel. To test this characteristic, the UAV was placed on the water surface loaded with weights and rocked to see if it would topple. The UAV remained stable during the tests.

To assess the vehicle's endurance to the impact on the water surface during an emergency landing, the UAV was dropped from different heights, ranging from $0.5\,\mathrm{m}$ up to $1.5\,\mathrm{m}$ with $0.25\,\mathrm{m}$ steps. Repeated with pitch angles of 0 degrees and 45 degrees, the UAV fell onto the water surface neither compromising its watertightness and buoyancy, neither damaging its frame, its propellers and their supports, or even the dome underneath.

Once the watertightness and robustness of the UAV were assured, the different locomotion modes were tested. Take-off and landing tests consisted on placing the UAV on the water surface, performing a take-off, hovering $1\,\mathrm{m}$ above the water, and landing back on the same spot (see Fig. 8). An operator repeated the procedure five times, having the UAV taking-off with ease and hover above the water surface, and landing back again smoothly without any damage to the vehicle. Next, the on-surface locomotion was tested by remotely controlling the UAV across the pool length using its own propulsion system. This test was carried out with and without motion opposing water currents induced by the pool's water injection system. In both situations the vehicle navigated smoothly and without any water flooding the electronics compartment.


(a) (b)

Fig. 9. The site of the field trials. (a) Satellite image of the testing area (dated from 2002). (b) Aerial image retrieved by the UAV during the field trials.

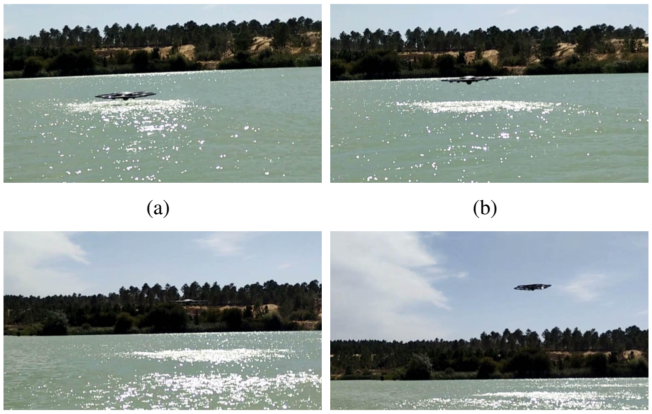

(a) (b) (c) (d)

Fig. 10. Sequence of snapshots taken during a take-off manoeuvre.

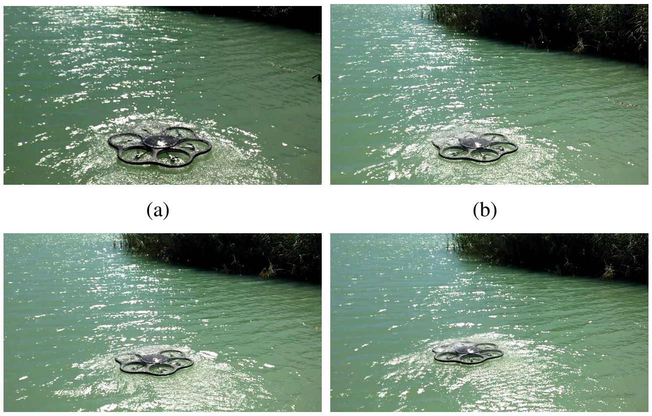

(a) (b) (c) (d)

Fig. 11. Sequence of snapshots taken while drifting on the water surface.

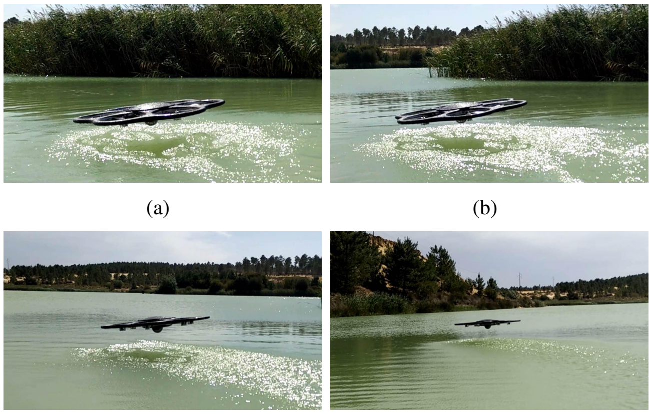

(a) (b) (c) (d)

Fig. 12. Sequence of snapshots taken while moving with ground effect.

B. *Field Trials*

The real world field trials were performed on a lake in Sesimbra, Portugal (see Fig. 9). The objective was to assert the capability of the UAV to operate in a sampling environment. The take-off/landing sequences performed on the pool were successfully repeated in the field trial, which shows that the procedure is robust enough for real world operation (see Fig. 10).

To be useful in real missions, the UAV needs not only to lift and land on the water surface but also to navigate in the environment and avoid obstacles. In this sense, longer flight tests were performed with the vehicle successfully flying from one area of the lake to another while taking-off and landing on the water's surface so as to overcome land present in the sampling path.

The on-surface locomotion method was also validated (see Fig. 11). The platform was remotely controlled to land on the water surface and then to move along a line of $15\,\mathrm{m}$, drifting along the lake surface. This type of locomotion showed to be feasible.

The use of ground effect for efficient flying near the surface was also tested. Ground effect in fixed wing aerial vehicles is felt while flying lower that half the wingspan of the aircraft [15]. However, despite the UAV's $0.3\,\mathrm{m}$ propellers, the ground effect on multirotors is present even at higher altitudes [16]. In the field trials, the UAV was able to exploit the ground effect to fly with reduced throttle input, suggesting an energy saving in the long run (see Fig. 12).

The water sealing of the UAV caused an expected rise in temperature that could affect the UAV reliability during a long lasting survey. Still, according to the flight controller's temperature log (see Fig. 13), no critical levels have been reached, thus validating the design. If such a critical level would be reached, then the UAV would engage on a landing procedure for cooling. The lowering of the temperature as a result of resting on the water surface was actually observed throughout the tests (see Fig. 13).

Finally, the chosen location for the field trials unveiled an interesting benefit of using watertight UAV's for in-situ water sampling in detriment of surface vehicles. The satellite imagery of this location (see Fig. 9(a)) shows a single water body to sample, whereas the imagery collected with the UAV's onboard camera shows that a sand bank now splits the water

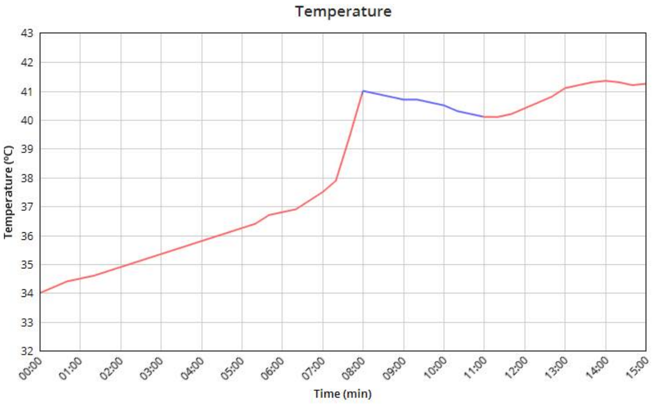


Fig. 13. UAV's electronic case temperature evolution while engaging different locomotion modes. The blue segment corresponds to the moment in which the UAV was resting on the water surface.

body impairing a surface vessel to sample the entire location (see Fig. 9(b)). By using the updated image the watertight UAV could plan a way to avoid the obstacle by leapfrogging from one water body to the other.

V. CONCLUSIONS

To enlarge the scope of environmental monitoring robotics in ecologically sensitive areas, an open-source watertight multirotor aerial vehicle capable of take-off and landing on both land and water was presented. The ability to operate in aquatic environments was attained by developing from the ground up a watertight structure with significant buoyancy and robustness to low-altitude crashes against the water surface. These properties result from using a carbon fibre sealed frame combined with low density core filling. In addition to the mechanical design, this paper also presented the hardware and software architectures responsible for ensuring take-off, landing, and waypoint navigation. To ease the expansion of the vehicle's capabilities and its integration onto larger robotic systems, the software architecture is built upon the ROS framework.

A set of field trials confirmed the watertightness and robustness of the structure to crashes against the water surface. Moreover, the tests also showed that the vehicle is able to smoothly take-off, land and, especially, move along the water surface by means of the same propulsion system used for flying. The experiments further confirmed the ground effect to be an efficient and controlled alternative locomotion method. The ability to land on water is key to handle emergency landings. The ability to move on the water surface enables long lasting water sampling by exploiting water currents. The ability to take-off and landing on water allows the vehicle to fly over obstacles, such as a dam or a large portion of land.

As future work, we expect to develop a set of autonomous behaviours capable of exploiting the water/land navigation capabilities of the presented vehicle towards energy efficient management. This includes controlling the aspects of each locomotion mode (e.g., motion on the water surface), determining the most suited locomotion method for a given context, and optimise the waypoints distribution to best exploit winds and currents when drifting on the water surface.

We also expect to fuse the abilities of the developed system with the long-lasting characteristics of the Riverwatch Experiment [6], allowing persistent monitoring of ecological relevant areas. A complete water sampling campaign is being prepared to further assess the accuracy and robustness of the system.

ACKNOWLEDGMENTS

This work was partially funded by the CTS multi-annual funding, through the PIDDAC Program funds.

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