Received: 27 February 2017 | Revised: 8 January 2018 | Accepted: 25 January 2018
DOI: 10.1002/rob.21777

SYSTEMS ARTICLE

WILEY

Loon Copter: Implementation of a hybrid unmanned aquatic–aerial quadcopter with active buoyancy control

Hamzeh Alzu'bi | Iyad Mansour | Osamah Rawashdeh

Department of Electrical and Computer Engineering, Oakland University, Rochester, Michigan, USA

Correspondence
Hamzeh Alzu'bi, Department of Electrical and Computer Engineering, Oakland University, Rochester, Michigan, USA.
Email: hmalzubi@oakland.edu

Funding information
This work was sponsored in part by the National Science Foundation (NSF) through award no. EEC-1263133, which is available to undergraduate students participating in a 10-week Research Experience for Undergraduates (REU) program at Oakland University in Rochester, Michigan.

Abstract
Aquatic–aerial unmanned vehicles recently became the focus of many researchers due to their various possible applications. Achieving a fully operational vehicle that is capable of aerial, water-surface, and underwater operations is a significant challenge considering the vehicle's air–water–air transition, propulsion system, and stability underwater. We present in this paper an unconventional unmanned hybrid aquatic–aerial quadcopter with active buoyancy control that is capable of aerial flight and water-surface operation, as well as subaquatic diving. We report on the first successful prototype of the vehicle, named the Loon Copter, to provide initial evaluation results of its performance in both mediums. The Loon Copter uses a single set of motors and propellers for both air and underwater maneuvering. It utilizes a ballast system to control vehicle buoyancy and depth underwater, as well as to perform seamless air-to-water and water-to-air transitions. A closed loop control algorithm is utilized for the vehicle's aerial and water-surface stability and maneuver, whereas an open loop control algorithm is used for underwater maneuver. The experimental results show a fully operational prototype with six degrees of freedom underwater, stable flight, operation capabilities on water surface, and agile maneuvering underwater.

KEYWORDS
buoyancy, control, propellers, unmanned aerial vehicle, unmanned aquatic-aerial vehicle, unmanned underwater vehicle

1 | INTRODUCTION

For the last two decades, unmanned aerial vehicles (UAVs) and unmanned underwater vehicles (UUVs) have been the focus of many researchers (Bouabdallah, 2007; Budiyono, 2009; Ferreira, Matos, Cruz, & Pinto, 2010; Iscold, Pereira, & Torres, 2010; Ranganathan, Thondiyath, & Kumar 2015; Ridao, Batlle, & Carreras 2001; Schmid, Lutz, Tomić, Mair, & Hirschmüller, 2014). The popularity of these types of vehicles will continuously increase due to their expanding availability and the cost efficiency of their production. These two kinds of vehicles were designed to perform well in their own specific environments. However, some situations require a vehicle to operate well in both aerial and underwater environments, such as mapping of remote regions, and inspection of submerse structures, such as petroleum platforms, ship hulls, and gas pipelines, as well as several military applications. (Drews, Neto, & Campos, 2009; Yang, Wang, Liang, Yao, & Liu, 2015) To fulfill this type of mission, the traditional UAV or UUV needs multivehicle collaboration. (Yang et al., 2015) An auxiliary vessel is currently used to transport the underwater vehicle to the goal location so it may dive to perform the inspection. However, this kind of operation is very expensive and inefficient. Moreover, it does not allow for simultaneously inspection of both the submersed and the nonsubmersed portions of the structure. A hybrid vehicle would be able to accomplish both more efficiently and at a lower cost. (Drews et al., 2009)

An aquatic unmanned aerial vehicle is a hybrid aircraft that has capabilities to operate in the air and in the water. (Siddall & Kovač, 2014) It possesses the advantages of UAVs and UUVs. The concept of manned hybrid aquatic–aerial aircraft was proposed in 1934. There have been few manned prototypes; none operated successfully in either the air or the water due to technical difficulties, including the compatibility of the structure in the two different mediums, the crew cabin, and the life support system. (Yang et al., 2015)

This article will further discuss the design and implementation of the vertical takeoff and landing (VTOL) hybrid aquatic–aerial Loon Copter. As the name implies, this vehicle possesses capabilities of flying in the air, taking off from the water, landing on the water, maneuvering on the water's surface (WS), and navigating underwater. A novel buoyancy control setup allows the Loon Copter to dive, surface, and loiter on the surface or underwater without the use of its propellers (Figure 1).

FIGURE 1 The Loon Copter functions in three modes of operation: the aerial mode (a), in which the vehicle operates as a conventional quadcopter; the surfacing mode (b), where the vehicle transits on the surface of the water; and the diving mode (c), where the vehicle propels underwater

There is currently some active research on hybrid aquatic–aerial vehicles, such as the hybrid aerial underwater vehicle, designed by the MIT Lincoln Lab. This design features a fixed-wing unmanned vehicle capable of flying, plunge diving into water, and navigating underwater by folding its wings. The vehicle can only transition from air to water, not from water to air. (Fabian, Feng, Swartz, Thurmer, & Wang, 2012) In addition, the Flimmer (Flying Swimmer) Program at the Naval Research Laboratory (NRL) produced a flying submarine, which also featured a fixed wing airplane. (Edwards, 2014) Both vehicles lack the ability to transition smoothly between air and water, as the transition at high speed creates a high impact on the vehicle's frame. This increase the complexity and cost of designing the vehicle's structure so that it can handle the impact force. On the other hand, the Loon Copter utilizes a ballast system to perform a seamless transition between the two media with simple airframe design. Some work involving multirotor-type drones is also underway. Drews, Neto, and Campos (2014) published a paper that modeled and simulated a multirotor type drone that uses two sets of propellers for a multirotor hybrid aquatic–aerial vehicle; one set for aerial flight and the other set for underwater maneuver. The vehicle will carry constantly the unused system, which would increase the power consumption, and the inactive propellers may add drag penalties. Lock, Vaidyanathan, and Burgess (2013) and Izraelevitz and Triantafyllou (2014) studied a bioinspired flapping foil with in-line motion to ensure efficient thrust production in different media. Both demonstrated the efficacy of this strategy in tunnel tests. Tan et al. investigated a single propeller with a gear box for both media; however, this increases the mechanical complexity and it risks power losses penalty due to the gear box friction. In contrast, the Loon Coper is a hybrid multirotor platform that uses a single set of propellers with direct drive in air and underwater, thereby reducing the vehicle's mechanical complexity and extra weight penalty.

The “Naviator” Drone (Maia, Soni, & Diez-Garias, 2015) was introduced at about the same time as the Loon Copter and is most closely related. The drone is an octacoaxial multirotor hybrid aquatic–aerial vehicle. The design makes use of four coaxial rotors with fixed pitch propellers. It is designed to be naturally buoyant, and uses the rotors to go underwater and to control the depth. All eight propellers are used to maintain or change depth as well as to maneuver underwater. One disadvantage of this approach is that it consumes significant power to maintain the vehicle's stability and depth underwater and to stay on the surface of turbulent water due to its static neutral buoyancy. The Loon Copter is different in that it is capable of actively controlling its buoyancy using a ballast system. This allows it to naturally loiter on the surface of water and then allows for submersion without the need for propellers to pull the vehicle underwater. The Loon Copter's ballast system allows the vehicle to suspend in a horizontal position underwater at a required depth and makes it capable of controlling the depth without use of propellers.

Interest in operating drones in and around water is also exemplified through the Corrosion Resistant Aerial Covert Unmanned Nautical System (CRACUNS) project. CRACUNS' vehicle is designed to be launched by an UUV, diver, or a fixed position underwater and to fly like an autonomous UAV. (Hopkins University Applied Physics Laboratory, 2016) The project is focused on the construction and testing of corrosion resistant drones. The designers fabricated a lightweight, submersible, composite airframe able to withstand the water pressure experienced while submerged. The vehicle's airframe is designed to sink in water, and it uses the propellers to control depth and maintain stability underwater, which would add power penalty on the rotors similar to other vehicles previously discussed. Also, it lacks the ability to park on the surface of water. On the other hand, the Loon Copter is designed with active buoyancy control, and it can control its buoyancy and maintain its stability without the need for the rotors. Results from the CRACUNS project are shaping to provide valuable references for constructing robust, corrosion resistant hybrid drones.

In 2014, we set out to design a hybrid drone, which we have now dubbed the Loon Copter. To achieve the Loon Copter's objectives of operations in aerial flight, surface, and underwater, we set out with the following main requirements:

- **(i)** Proper vehicle waterproofing.
- **(ii)** Air and underwater stability and capability of buoyancy adjustments for a seamless transition between air and water, as well as to control depth underwater.
- **(iii)** Minimal load on the vehicle's power-plant underwater.

This paper provides a description of the design and discusses results and possible future improvements and modifications. Section 2 begins by providing a high-level overview of the quadcopter. Section 3 introduces the vehicle's technique for air–water–air transitioning and achieving stability underwater. In Section 4, we evaluate

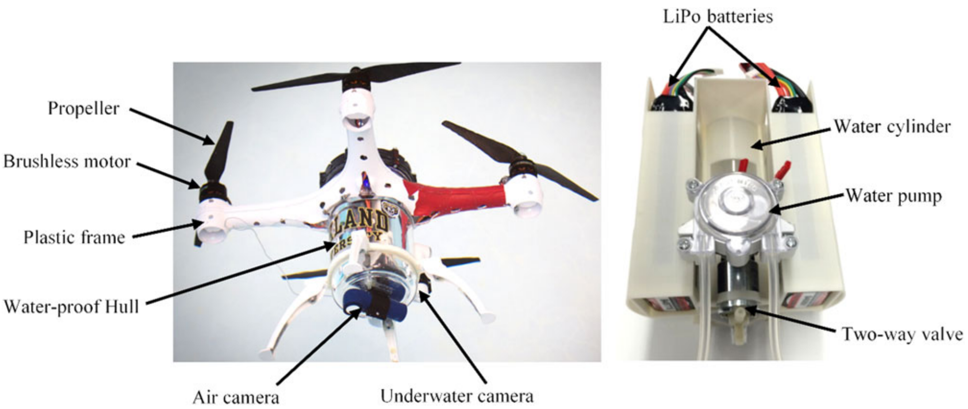

FIGURE 2 Loon Copter external and internal components: external components (left) consist of water-proof hull, cameras, four brushless motors with four propellers, and plastic frame. Internal components (right) consist of lithium polymer batteries, water pump, water cylinder and two-way valve, as well as four speed controllers, flight controller, and pump controller which are not shown

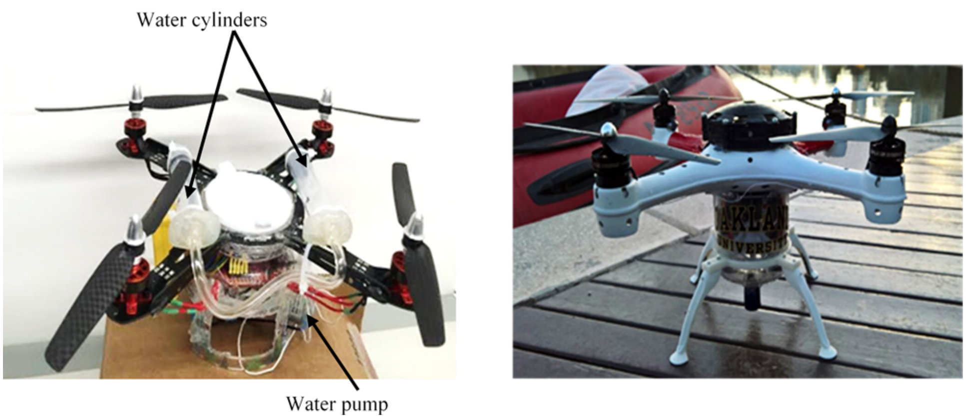

FIGURE 3 Loon Copter first 2014 prototype (left) and current 2016 prototype (right)

the aerial power-plant for use underwater. Lastly, Section 5 explores the vehicle's electronics and control systems. We then discuss the performance of the vehicle and conclude the paper.

2 | HYBRID AQUATIC–AERIAL QUADCOPTER OVERVIEW

The Loon Copter consists of the following main components, as shown in Figure 2 a water-proof hull, four sealed-bearing motors with four fixed-pitch propellers, two lithium polymer (LiPo) batteries, a plastic frame, a ballast system, four speed controllers, and an avionics system. Two cameras are also attached as a payload for surveillance, one for air and one for underwater. The vehicle's frame is constructed out of a plastic hull for cost efficiency and ease of manufacturing. The rotors consist of waterproof brushless motors and carbon fiber fixed-pitch propellers. The depth control system is comprised of a water pump, a two-way valve, a water cylinder, and a water pump controller. The avionics system is a Multiwii pro flight controller. As a power source, two LiPo—3600 mAh (14.8 V) batteries are used to power the motors and the avionics.

Figure 3 shows the vehicle's first prototype, successfully tested in 2014, and the current prototype of the Loon Copter. The first prototype was designed to assess the feasibility of developing a hybrid unmanned aquatic–aerial quadcopter. The field test* of the vehicle's first prototype demonstrated promising results of our novel hybrid VTOL drone, which was able to fly, surface, and dive underwater. After experimentally analyzing the vehicle's performance, it was obvious that the transition between air and water needed enhancement to improve the vehicle's stability underwater. As shown in Figure 3, the ballast system of the first prototype was mounted on the hull externally, and the water cylinders (consisting of two syringes) were mounted horizontally on the vehicle's airframe directly under the propellers. This lack of symmetry of the vehicle's frame made the vehicle difficult to control underwater. Based on the first prototype results, the current prototype was developed to enhance the Loon Copter's design and controllability underwater. As shown in Figure 3, the current prototype has a cleaner frame compared with the first prototype, which was achieved by moving the ballast system inside the hull. This also had a major effect on the vehicle's stability underwater since the buoyancy force depends on the shape of the vehicle. The detailed operation of the ballast system is discussed in Section 3.2. Experimental tests† show that the current design produced a fully operational prototype.‡

* Hybrid aquatic–aerial quadcopter first prototype test: http://youtu.be/5pV32tLSv8Y

† Test of the Loon Copter current prototype: https://www.youtube.com/watch?v=STRijGJ5qtI

‡ Loon Copter won the 2016 UAE Drones for Good competition in Dubai. The UAE Drone for Good Award: http://www.dronesforgood.ae/

The three operation modes of the drone were tested in indoor and outdoor environmental conditions. A calm swimming pool was used for water-surface and underwater tests. In the outdoor test, the average wind speed was about 13 kph. This speed barely affected the condition of the pool; however, small waves were created due to water-surface operation. The vehicle flight tests were performed in hover mode for both indoor and outdoor conditions, and the lowest batteries voltage reached was 14.6 V to avoid damaging the LiPo batteries. The vehicle's average outdoor flight time was about 10.5 and 12 min for indoor flight. Obviously, the difference in flight time was due to wind effects. The average underwater operation time was 22 min, with an average underwater speed of 0.5 m/s. Moreover, the average water-surface operation time for both indoor and outdoor tests was about 20 min with an average speed of 1.0 m/s. The total operation time of the Loon Copter was about 15 min for the three operation modes, with about 8 min of flight time. Using the ballast system, the vehicle could suspend for about 11 h underwater without propellers. The maximum communication link underwater between the vehicle and the remote controller was 3 m in depth and 10 m horizontally. The Loon Copter's air–water transition time was about 25 s, and the water–air transition time was about 13 s. The current prototype weight with payload is 2.7 kg.

3 | LOON COPTER TRANSITION AND STABILITY UNDERWATER

The vehicle's transition between air and water, as well as stability and depth control while underwater, must also be examined. The following subsections will consider the details of aerial to underwater control.

3.1 | Buoyancy and depth control

UUVs can dive in one of two ways: static and dynamic. The static diving system utilizes a ballast system to dive and surface the vehicle without any forward movement, whereas dynamic diving uses control surfaces or rotors to force the vehicle to dive underwater. There are four concepts within these two diving systems:

- **i)** An air compressor-based ballast system.
- **ii)** A hydraulic pump-based ballast system.
- **iii)** A piston tank ballast system.
- **iv)** A direct thrust system.

The first three concepts are classified as static diving systems, whereas the latter concept is a dynamic diving system. (Wang, Chen, Marburg, Chase, & Hann, 2008)

The Loon Copter's depth and transition control system design employs a combination of a hydraulic pump-based ballast system and piston tank ballast system to achieve a seamless air–water and water–air transition and to reduce power load on the vehicle rotors. This static diving system allows for control of the vehicle's depth underwater, as well as enables the vehicle to flip 90° with minimal power consumption compared with dynamic diving. This system was created because of its simple design, easiness to control, and flexibility to distribute the system components on the vehicle frame. As shown in Figure 4, the Loon Copter's ballast system consists of the vehicle's hull, a water cylinder, a movable piston, a two-way valve, and a water pump. The hull of the vehicle is used to mount the ballast system components as well as to hold the compressed air. In addition, the movable piston is used to hold the water in the water cylinder during diving, which improves the vehicle's stability. The water cylinder capacity is 150 ml, about 100 ml is used to submerge the Loon Copter underwater and the rest is utilized to control depth. The two-way valve is needed to hold the water in the water cylinder, as the compressed air inside the hull will attempt to push the water out of the cylinder when it is underwater. The Loon Copter utilizes the ballast system without the vehicle's rotors to perform the two-media transition and to control depth. A data logger and power sensor were used to measure the power consumption of the Loon Copter's ballast system, as it performed transition and maintained the vehicle underwater, versus its rotors. The ballast system consumes 6 W, whereas the rotors consume 450 W, which is a significant amount of power to perform transition and to maintain the vehicle underwater. Even though the ballast system costs the Loon Copter about 1 min of flight time, it saves a significant amount of power to suspend the vehicle and to control depth underwater compared with the vehicle's rotors.

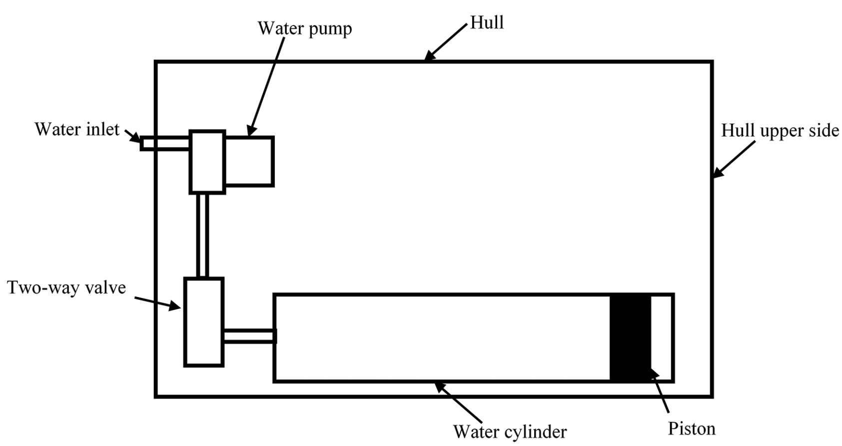

FIGURE 4 Loon Copter's hull side view showing ballast system

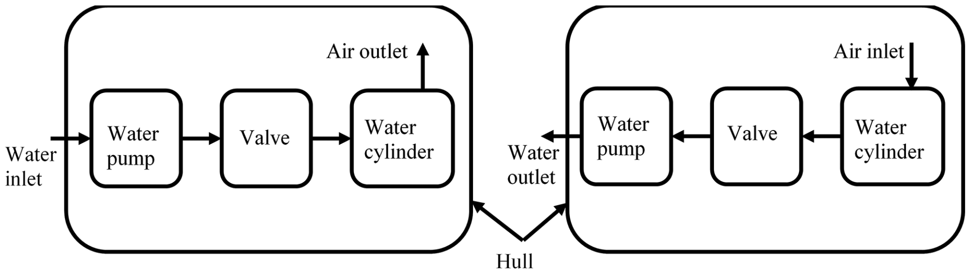

FIGURE 5 Air–water transition water flow (left): the water pump moves the water through the valve to the water cylinder until the vehicle submerges underwater. Water–air transition water flow (right): to restore the vehicle to the water surface, the water pump moves the water from the water cylinder through the valve

Figure 5 shows the water flow direction when the vehicle transitions between the two media. While the vehicle is on the WS, the water cylinder and the hull will have a certain amount of air at ambient pressure. The vehicle's transition will begin as water is pumped into the water cylinder from the water inlet. As the water cylinder is filled with water, the air inside the cylinder will move to the vehicle hull, which will become pressurized by the addition of water. When the water cylinder is filled, the Loon Copter will start to tilt 90° and submerge simultaneously. Similarly, the vehicle's water–air transition will occur when the water cylinder is emptied, which will cause the Loon Copter to float to the surface of the water and revert back to its upright position.

3.2 | Center of buoyancy and center of gravity control

This subsection discusses the relationship between the center of gravity and the center of buoyancy of the Loon Copter and its effect on stability. Buoyancy is the upward force asserted on an immersed or floating body by the supporting fluid. This conception of the term conveys the idea that volume, alone, determines buoyancy and that the upward force exerted on the immersed or floating body equals the weight of the fluid that it displaces. (United States Navy, 2008) Given this property, tilting the vehicle underwater while maintaining its stability is considered a major challenge due to the location of the center of gravity relative to that of the center of buoyancy. The stability of the vehicle depends on the relative lines of action of the two centers. Thus, the center of buoyancy must be precisely above the center of gravity; otherwise, the vehicle will be unbalanced in terms of roll and/or pitch moment. To reduce the power requirements of the Loon Copter stability and underwater maneuvering, the Loon Copter's ballast system is used to control the depth of the vehicle and to tilt the airframe of the vehicle such that its rotors are perpendicular to the surface of the water.

The vehicle's primary stability underwater depends mainly on the center of buoyancy and the center of gravity. The Loon Copter's air–water transition is illustrated in Figure 6. Figure 6a shows the vehicle's landing on the WS. As notated in this figure, there are three centers on the line of action: the metacenter (M), the center of buoyancy (C_b), and the center of gravity (C_g). The metacenter is the point of intersection of a vertical line with the center of buoyancy of the Loon Copter body, with the vertical line through the new center of buoyancy when the body tilts. If C_b and C_g are on the same line of action, the Loon Copter will level horizontally. On the other hand, if one of the centers shifts from the line of action, a rolling moment will be created that will tilt the vehicle. Figure 6b captures the effect of the rolling moment. When water begins to pump to the cylinder, the C_g will shift to the left, and by continuing to pump the water, C_g will shift enough that it will make the Loon Copter tilt ∼90° relative to WS and dive. The final state after transition is completed is shown in Figure 6c.

When the vehicle is on the surface of the water, the metacenter will be above C_b and C_g. If some disturbance attempts to move the vehicle from the equilibrium position, a moment will be created around M to restore the vehicle to its original position. When the Loon Copter is completely submerged C_b and M will be at a common point. After the Loon Copter reaches the 90° position underwater, the C_b and C_g will lie on the same line of action.

As shown in Figure 4, the ballast system was designed with the water cylinder placed alongside the hull of the Loon Copter, which aids in the transition and stability of the vehicle underwater. As the water cylinder fills with water, the center of gravity becomes below the center line of the airframe. If some underwater turbulence disrupts the vehicle from its equilibrium condition, a moment will be created around M to restore the vehicle to its original position. When the Loon Copter is in the air, the center of gravity is located just below the propellers, like in a conventional aerial quadcopter, which allows for stability while the vehicle is in flight.

4 | LOON COPTER POWER PLANT EVALUATION

This section will evaluate the preliminary feasibility of using aerial, fixed-pitch propellers underwater. Various tests were performed both in air and water using a test stand designed to study the thrust to power ratio of commercially available, counter-rotating, multirotor propellers.

As shown in Figure 1, the Loon Copter makes use of one set of propellers to both fly and move underwater. This objective ultimately reduces the complexity and weight of the vehicle. On most aerial/aquatic vehicles, propellers are designed to operate efficiently in various mediums with different densities and viscosities, and therefore have distinct properties. Thus, in the context of combining propeller usage for operation in air and underwater, cavitation, or the formation

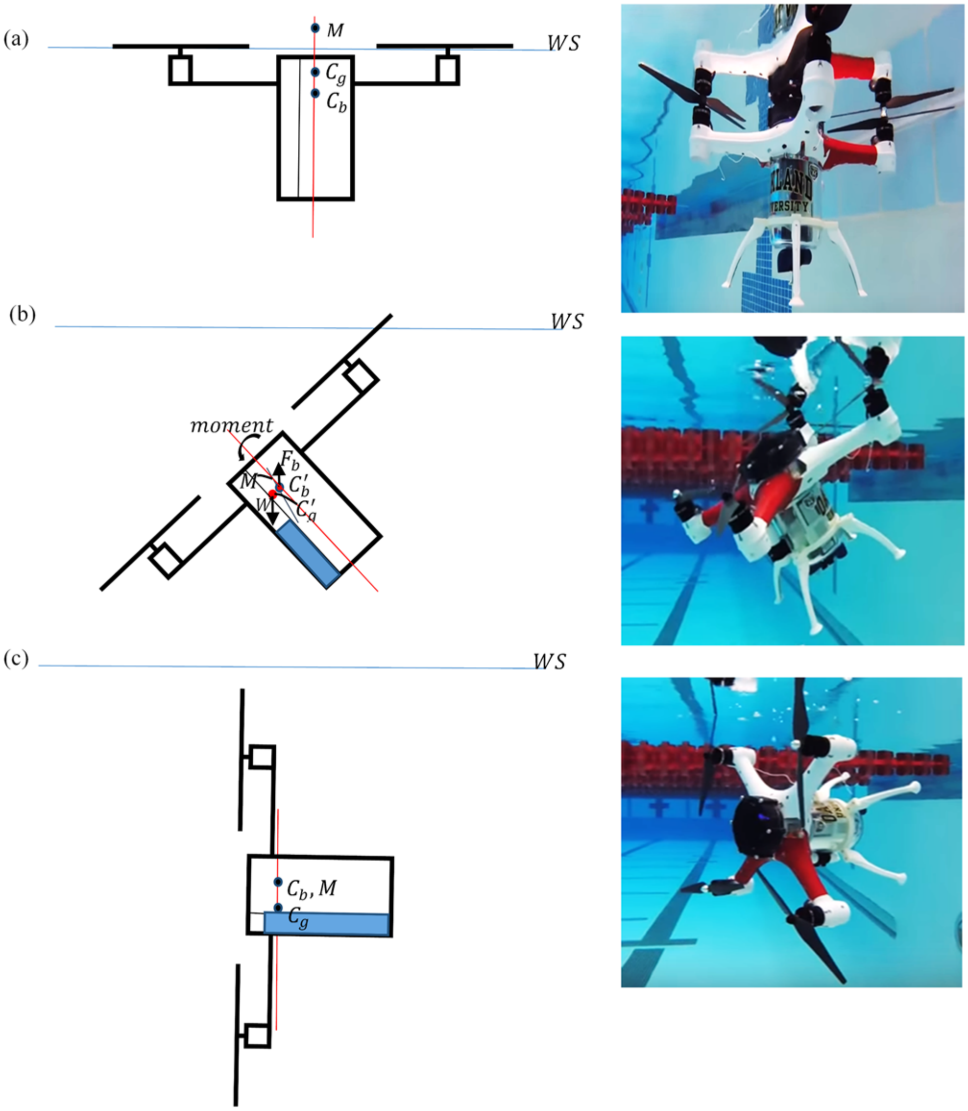

FIGURE 6 Loon Copter air–water transition. Subfigures (a) shows the Loon Copter's landing with its rotors are parallel to the water's surface (WS), (b) illustrates the vehicle's air–water transition, and (c) presents the final state of the vehicle, where the Loon Copter suspends horizontally underwater

of vapor bubbles in water near a moving blade, becomes a challenge. Such bubbles bursting may result in shockwaves being sent back to the propellers, causing the propellers to erode. This phenomenon, though, usually occurs at high speeds. Nevertheless, from a theoretical standpoint, air and water propellers will behave similarly, essentially in the interest of operating air propellers at low Mach numbers (where compressibility effects are negligible) and water propellers operating without cavitation. (Kerwin, 1986)

The main parameters that describe thrust and power of a propeller are shown in the following equations (Drews et al., 2014):

$$T = C_T \rho \omega^2 D^4 \tag{1}$$

$$P = C_P \rho \omega^3 D^5 \tag{2}$$

where T is the thrust (Newtons), P is the propulsion power (Watts), ρ is the environment density (kg/m^3), ω is rotation speed (revolution per minute – rpm), D is the propeller diameter (m), C_T is the thrust coefficient, and C_P is the power coefficient. These two equations describe the essential parameters that are needed to calculate the thrust and power of a propeller in both air and water mediums. Based on these two equations, a test-stand was developed to experimentally calculate the thrust and power in order to study the propeller's performance. For each test, C_T, C_P, ρ, and D were fixed constants and the variable ω was adjusted. The total thrust to electrical power consumption was calculated based on experimental measurements.

The propeller test stand, shown in Figure 7, was built using commercially available components. It is comprised of a data logger to collect test data, a thrust meter (scale) to measure thrust, a rotor, an Arduino board, an rpm sensor, a power sensor, and a thrust measurement mechanism. The rotor is a brushless motor (model dji 2212/920 KV) with a variable pitch propeller (model varioprop 8″ by 3″ - 4.75″) as the Arduino board was programmed to run the brushless motor

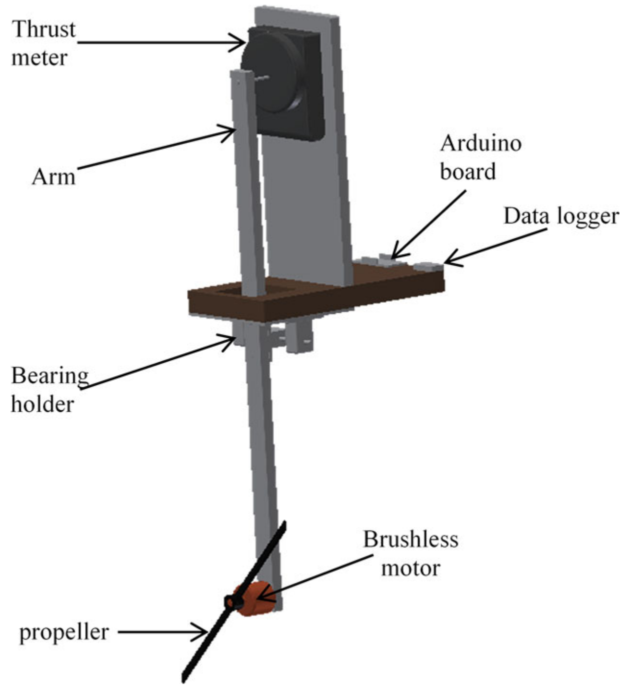

FIGURE 7 CAD model of the propeller test stand

at different speeds. The data points of power, thrust, and rpm were collected at each speed. The propeller was tested underwater in a rectangular plastic tank, 0.75 m long by 0.55 m wide by 0.50 m deep. The tip of the propeller was 20 cm under the WS.

As shown in Figure 7, the thrust measurement mechanism was designed to measure the rotor's thrust. This mechanism contains a bearing and an aluminum arm. The rotor is attached to one end of the arm, while the scale is on the other end with both of them equidistant to the bearing. When the rotor pulls the arm, the arm rotates around the bearing and creates force on the scale. This force is the thrust produced from the rotor.

Figure 8 shows the test results of the variprop propeller starting at a 3″ pitch angle and adjusting through 4.75″ pitch angle in 0.25″ increments. Depicted on the left-hand side of Figure 8 are the propeller's measurements in the air test, whereas the right-hand side displays the measurements for the tests underwater. As expected, it was found that, as the rpm of the propeller increase, the thrust and the power consumption also increase. Furthermore, the thrust to power ratio increased until it reached a maximum rpm (180 rpm for underwater and 4000 rpm for air on average) for each pitch angle. As shown in subfigures (a)–(d), there is a proportional relationship between thrust, power consumption and pitch angle in both media. Also, from subfigures (e) and (f), we notice that the thrust to power ratio in aerial tests is proportional to pitch angle; on the other hand, the thrust to power ratio has a contrary relationship with pitch angle in underwater tests. In subfigures (b), (d), and (f), the aerial rotor generates the cavitation phenomenon at about 200 rpm rotor speed, and the experimental data shows that the power consumption increased significantly, which negatively affected the thrust to power ratio. Subfigure (f) shows that pitch angle 3.0″ was the best among the angles in terms of the force generated to power consumed, with maximum thrust to power ratio of 0.26 N/W underwater. Subfigure (e) illustrates that pitch angle 3.75″ was the best, with maximum thrust to power ratio of 0.085 N/W for aerial tests. It is obvious that using an aerial propeller with low pitch angle is more efficient for underwater operation and that a higher pitch angle is better for aerial flight. We considered different propulsion system designs to use small pitch angle underwater and high pitch angle in air, such as a variable pitch propeller, or the possibility of using two separate propellers, one for air and the other for underwater. Also, Tan, Siddall, and Kovac (2017) suggested a single aerial propeller with a gear box to reduce the power load on the rotor, and to avoid damaging the brushless motor. However, his results are questionable as they were based on simulation. All those alternatives would add significant mechanical complexity and weight penalty on the rotors, which makes this challenging to implement. We chose to use a single fixed pitch propeller with direct drive to make the design simple and to reduce the extra weight penalty. Moreover, the experimental results show that the power consumption at low speed without cavitation underwater is comparable to the power consumption in aerial flight. For example, at 3.75″ pitch angle, the aerial power consumption is 10.57 W and thrust is 0.87 N at about 4000 rpm, whereas the underwater power consumption is 8.14 W and thrust is 1.33 N at about 200 rpm. Based on the test results shown in Figure 8, it can be deduced that the thrust, power consumption and efficiency curves have similar patterns in both air and water. In addition, it was found that the aerial propeller was efficient at a low rpm without cavitation. Based on these test results and Equations (1) and (2), we conclude that the behavior of the aerial fixed pitch propeller underwater at low speed is similar to its behavior in the air, and it can provide enough thrust for movement and maneuver underwater. Therefore, the 12″ × 3.8″ aerial fixed pitch propellers prove to be the most advantageous option for the Loon Copter vehicle. Since each of the vehicle's rotors could generate 12 N thrust at 800 rpm, and the ballast system is used to suspend the vehicle underwater the generated amount of thrust is sufficient to move the vehicle underwater.

The chosen power plant (motor–propeller combination) is quite common for drones of the Loon Copter's size and weight, and therefore resulted in minimal penalty in terms of flight time in air. The power plant was also extensively tested underwater. The current limit of the Loon Copter's rotor is 40 A, and the maximum current drawn underwater at 800 rpm is 7 A. Therefore, no mechanical fatigue, temperature, or motor controller overloading issues were found when the speed was limited to 800 rpm underwater. At higher speed, the brushless motor experienced cogging due to overload, and thus the speed controller of the motor shut down, which is the reason for limiting the maximum rotational speed of the rotors. Piccoli and Yim (2016) suggested an anticogging algorithm to reduce the effect of cogging torque on the brushless motor by improving the software of the motor speed controller, which may be used in future development. Nevertheless, each of the vehicle's rotors could generate about 12 N thrust at 800 rpm and thus limiting the speed of the motor reduced the effect of this limitation. Using the chosen power plant provided adequate thrust to fully maneuver the vehicle when submersed. Lateral speed underwater may be restricted due to the limited thrust and drag of the vehicle; however, it was deemed reasonable considering the vehicle's capacity to

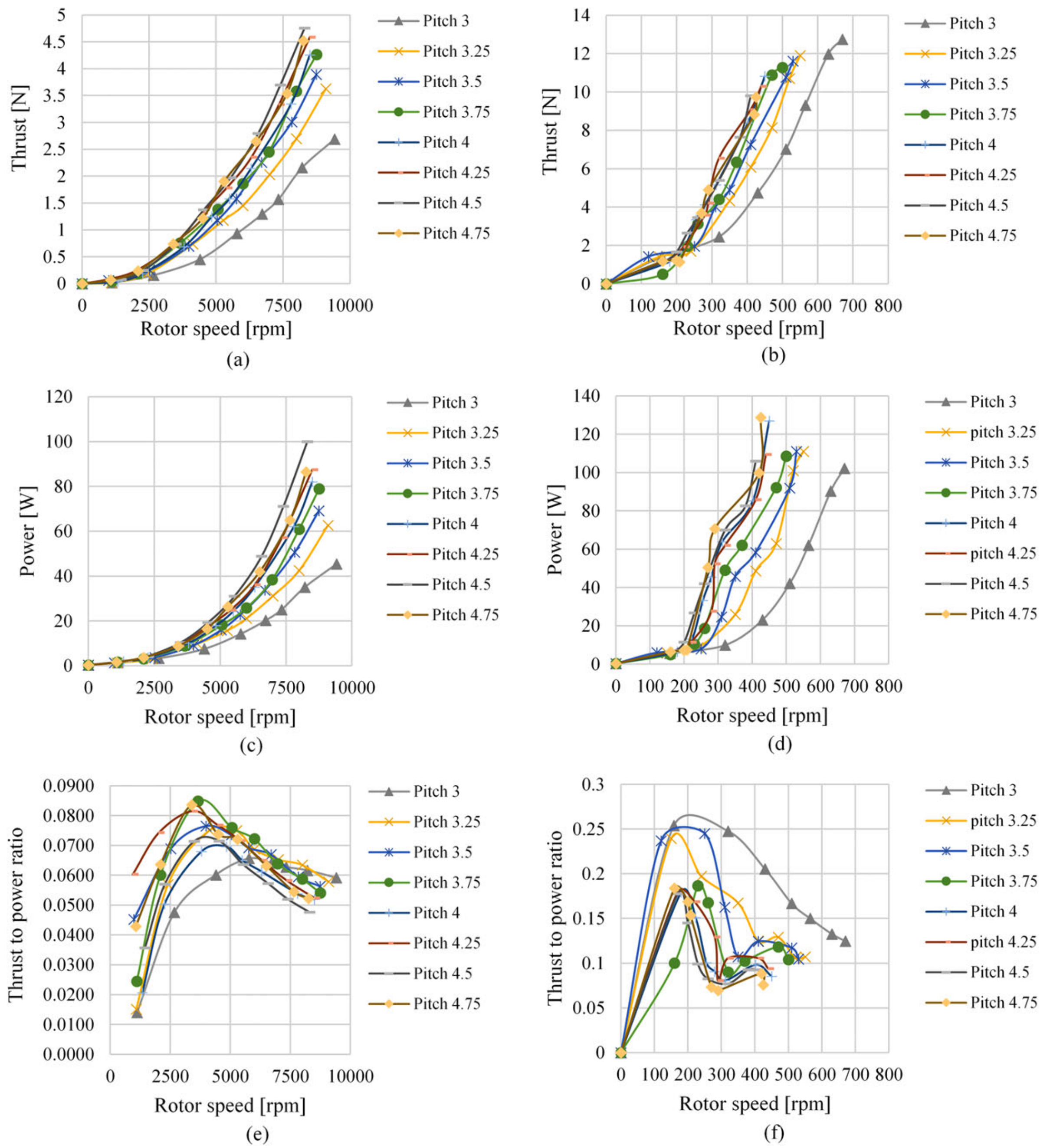

FIGURE 8 Propeller's data analysis in the air (left) and in the water (right). Subfigures (a) and (b) represent the thrust versus rotor speed, (c) and (d) show the power consumption versus rotor speed, and (e) and (f) show the thrust to power ratio in air and underwater, respectively

surface and cover larger distances in air before diving again at a desired location.

5 | LOON COPTER ELECTRONICS AND PERFORMANCE

The Loon Copter's avionics system is comprised of the following:

- **i)** A Multiwii pro open source flight controller is used to control multirotor RC models. The Multiwii hardware consists of a single ATmega 2560 microcontroller and an Inertial Measurement Unit (IMU).
- **ii)** A low frequency, Futaba 72 MHz, RC transmitter, and receiver is used to communicate with the Loon Copter underwater.
- **iii)** A water pump speed controller, Viper Marine 10, is used to control the ballast system.
- **iv)** Four brushless speed controllers, Castle edge 50, are used to control the waterproof brushless motors.

The diagram of the avionics system wiring is provided in Figure 9. The Mutiwii controller receives the flight command signals from the RC receiver. Then, this controller generates the control signals to stabilize

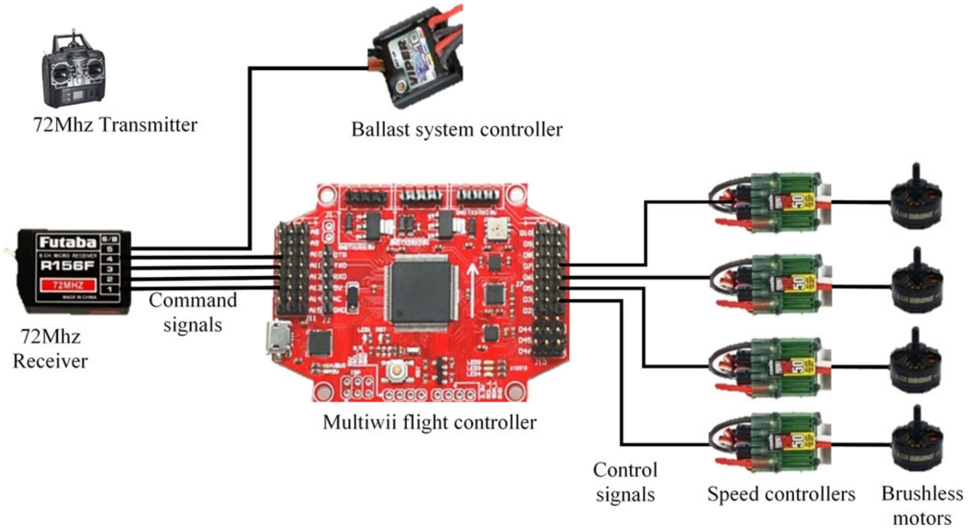

FIGURE 9 Loon Copter electronics wiring diagram

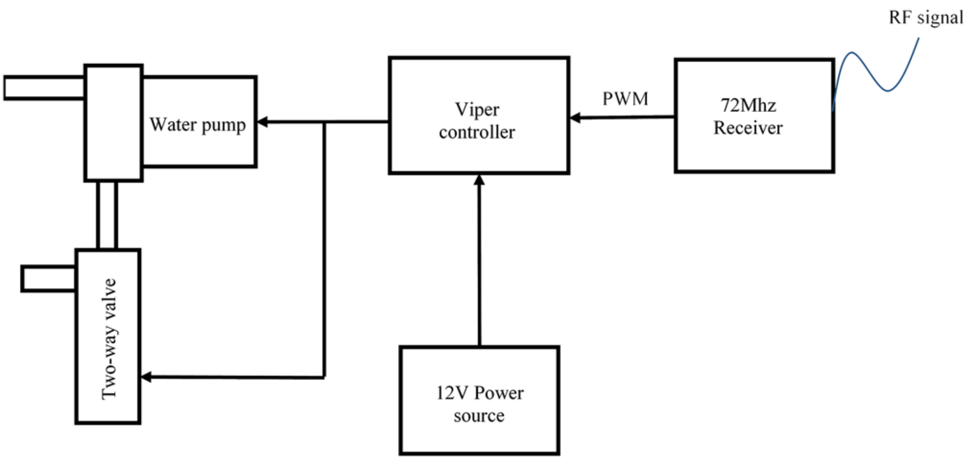

FIGURE 10 Loon Copter ballast system wiring diagram

and maneuver the Loon Copter. In addition, the water pump controller receives the command signal directly from the RC receiver to control the ballast system.

5.1 | Depth control electronics

The wiring diagram of the ballast system's depth control is shown in Figure 10. A 12 V power supply is used to power the water pump speed controller, which is used to control the water pump and a two-way valve. Both the water pump and the two-way valve are wired to the same output of the water pump controller.

The ballast system is designed to move the Loon Copter in the heave direction underwater. When the vehicle completes the air-water transition and submerges in water, the amount of water in the water cylinder can be adjusted to control the depth and to keep the vehicle suspended at the required depth. As shown in this figure, the speed controller receives the pulse width modulation (PWM) from the RC receiver to control the two-way valve and the water pump simultaneously. A three-position switch is used to generate the required PWM that controls the direction and the speed of the water pump and the direction of the two-way valve. This switch generates three different values of the PWM: 1 ms, 1.5 ms, and 2 ms. When the water pump controller receives a 1 ms PWM signal, it opens the valve and rotates the water pump in a clockwise (cw) direction to pump the water into the water cylinder. When it receives a 1.5 ms PWM signal, it turns off the water pump and closes the two-way valve. Lastly, when the controller receives a 2 ms PWM signal, it opens the valve and rotates the water pump in a counterclockwise (ccw) direction to pump out the water.

5.2 | Attitude control and stability

The Loon Copter has two control modes: an aerial mode and an aquatic mode. In both modes, the Loon Copter is controlled remotely using the RC transmitter. The transmitter consists of six channels: four channels to command the vehicle throttle, pitch, roll, and yaw. The remaining two channels are two switches, one of which is used to switch between the air and water mode, whereas the other switch is used to control the ballast system. An open source PD control algorithm was implemented to stabilize the vehicle in the aerial mode. However, the PD gains were altered to achieve stability in air. In the aquatic mode, an open loop

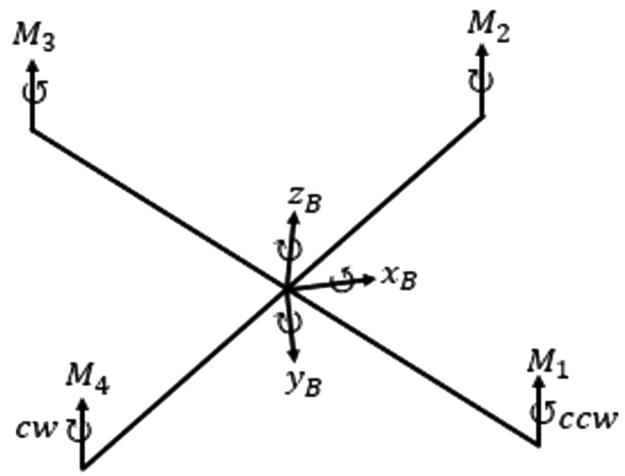

FIGURE 11 Loon Copter axes definition in aerial mode. x_B, y_B, and z_B represent the roll, pitch, and yaw, respectively, of the Loon Copter's body frame

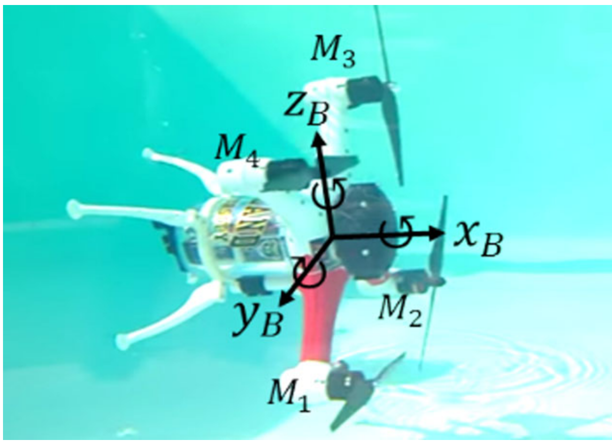

FIGURE 12 Loon Copter's body frame underwater. The vehicle's roll, pitch, yaw, surge, and sway are achieved using the rotors, while the heave is performed using the ballast system in the direction of z_B

control algorithm is used underwater since the stability of the vehicle is achieved by the ballast system.

The vehicle's body frame, shown in Figure 11, is specified with x_B, y_B, and z_B axes. These represent the roll, pitch, and yaw axes, respectively. The Loon Copter is a cross-type quadcopter, that is, to control pitch and roll axes, all the rotors contribute in generating the forces and moments necessary to stabilize and control the vehicle.

As shown in Figure 11, M_1 and M_2 are located in the front of the vehicle, whereas M_3 and M_4 are located in the rear of the vehicle. M_1 and M_3 rotate in a ccw direction, and M_2 and M_4 rotate in a cw direction.

The vehicle has 6 degrees of freedom (DOF) underwater. It has 5 DOF roll, pitch, yaw, surge, and heave and one DOF as sway is coupled with yaw. As shown in Figure 12, when the four motors (M_1, M_2, M_3, and M_4) are actuated with the same angular velocity, the vehicle moves in the surge direction. Pitch is achieved by increasing the angular velocity of motors M_1 and M_2 and simultaneously decreasing the angular velocities of motors M_3 and M_4. Similarly, yaw and sway are achieved by increasing the angular velocity of motors M_1 and M_4 and simultaneously decreasing the angular velocities of motors M_2 and M_3. Roll is performed by increasing the angular velocity of motors M_2 and M_4 and simultaneously decreasing the angular velocities of motors M_1 and M_3. Heave can be achieved using the ballast system while the rotors are stationary, or it can be coupled with pitch.

5.2.1 | Loon copter flight control

Figure 13 shows the Loon Copter's avionics control system. The system includes two main components: the attitude PD controllers and the four motor command mixers. The PD controllers are roll, pitch, and yaw. The aerial altitude control is also open loop and is controlled directly from the RC transmitter. The command mixing blocks are for the front right, front left, rear right, and rear left motors (M_1, M_2, M_4, and M_3, respectively). For instance, to command the vehicle to roll right, the mixing blocks will reduce the rotational speed of M_1 and M_4, and increase that of M_2 and M_3. The feedback states are received from the onboard inertial measurement unit. Commands from the remote pilot include the desired pitch, roll, and yaw angles, in addition to the desired altitude. Each PD controller calculates the difference between the feedback and the reference and tries to eliminate errors. The output of each controller is mixed in the four mixing blocks to produce the desired PWM signals and to send them to the motor controllers in order to achieve the desired speed for each of the motors. Figure 14 shows the Pitch PD controller as an example of one of the PD controllers used in the avionics system. Figure 15 illustrates the experimental results of the Loon Copter hover flight test. Subfigures (a), (b), and (c) represent the Loon Copter's roll, pitch, and yaw attitude test results, respectively. The PD controller has to maintain the vehicle's attitude angles at zero in flight within $\pm 2°$ error. As shown in subfigure (c), the yaw angle has some drift due to the vehicle's magnetometer sensor noise. However, the Loon Copter is stabilized despite these disturbances.

5.2.2 | Loon copter surfacing

The air mode control algorithm is also used for the vehicle's operation on the surface of water. The Loon Copter is positively bouyant. When it lands on water, it floats and can be remotely controlled to move on the surface of water.

As shown in Figure 16, the maximum pitch angle (α) for the Loon Copter surfacing mode is 15° relative to WS when the hieght (l) of the vehicle is about 13 cm above the WS. The vehicle's maximum surfacing speed at these configurations was about 1.5 m/s.

5.2.3 | Loon copter transition and suspension underwater

The experimental results of the Loon Copter's air–water and water–air transitions are shown in Figure 17. An IMU sensor was used to measure the vehicle's tilt angle relative to the WS. Depicted on the left-hand side of Figure 17 are the vehicle's tilt angle measurements for the air to water transition test, whereas the right-hand side displays the water to air transition test measurements.

The water–air transition takes less time compared with the air–water transition. As shown in the left figure, the vehicle takes about 8 s to start submerging underwater because some parts of the vehicle

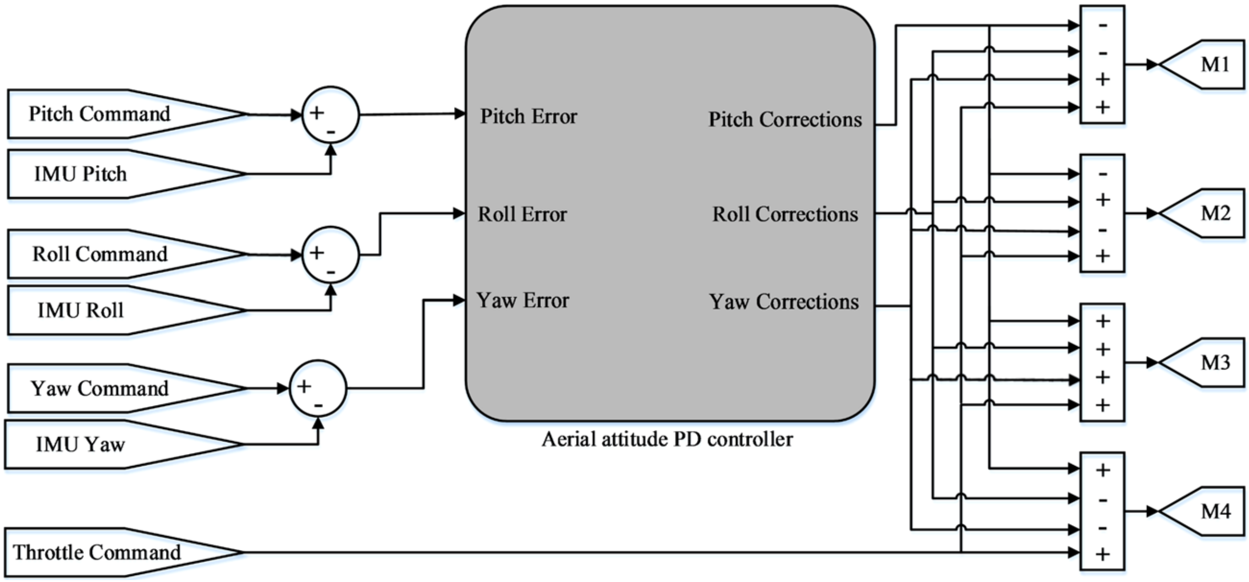

FIGURE 13 Block diagram of aerial mode control algorithm

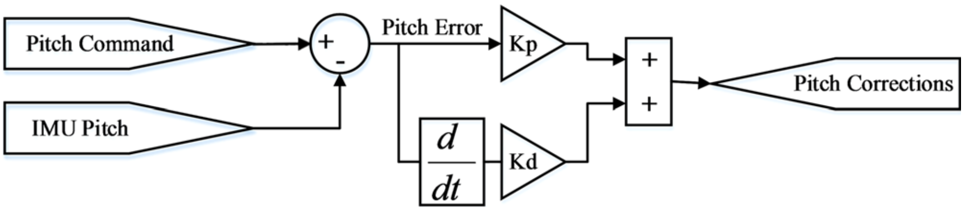

FIGURE 14 Pitch PD control block diagram

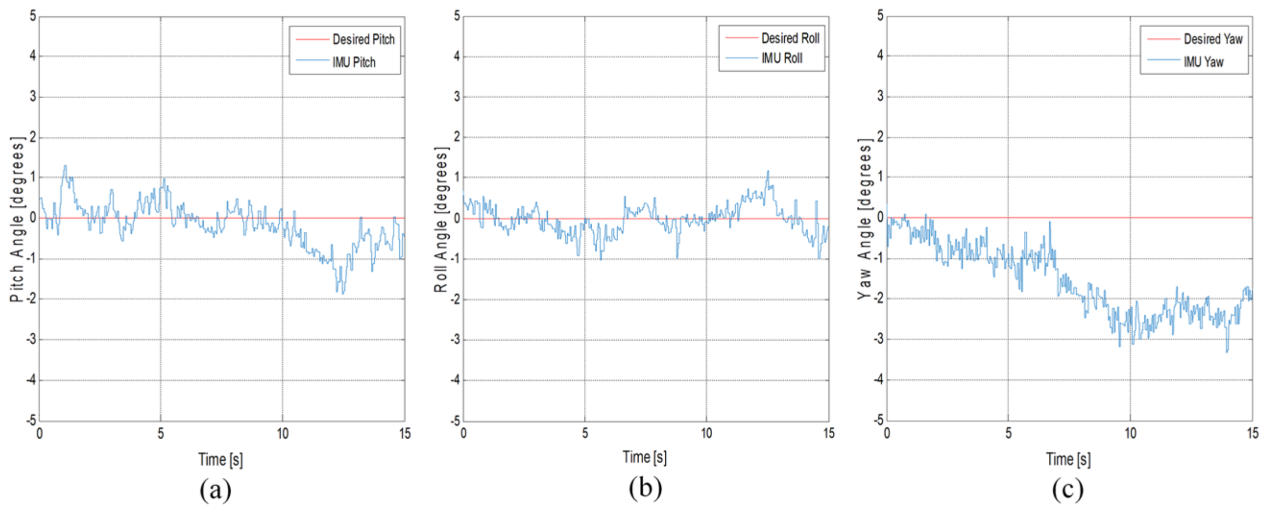

FIGURE 15 Loon Copter's hover flight. Subfigures (a), (b), and (c) illustrate the vehicle's pitch, roll, and yaw test results, respectively

are initially out of water. This requires the ballast system to pump in enough water to make the density of the vehicle higher than the density of water. At 10 s, the vehicle starts tilting and submerging slowly; when the vehicle becomes fully submerged at 15.8 s, it tilts quickly. The overshoot apparent in Figure 17 occurred because an extra amount of water was pumped into the water cylinder which makes the vehicle tilt to 106° relative to the WS. This was adjusted by releasing a small amount of water from the water cylinder, which makes the Loon Copter suspend at about 90° underwater. When the ballast system releases the water, the vehicle slowly restores its level position. As shown in the right figure, at 11 s, part of the vehicle exits the water, which affects the relative positions of the center of buoyancy and the center of gravity. This makes the vehicle's water to air transition instantaneously unstable. At approximately 12 s, the vehicle's rotors were pulsed to restore the transition stability, which makes the Loon Copter float on the surface of the water to its level position. After the transition to air is

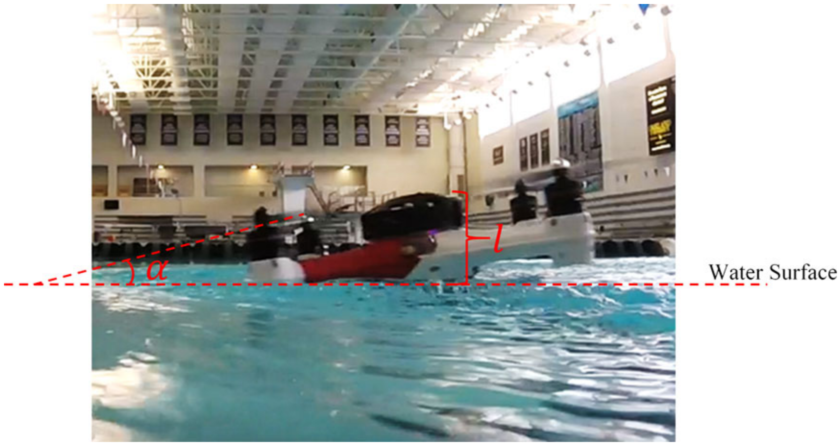

FIGURE 16 Loon Copter maximum surfacing angle (α) relative to water surface. The vehicle's maximum angle depends on the height (l)

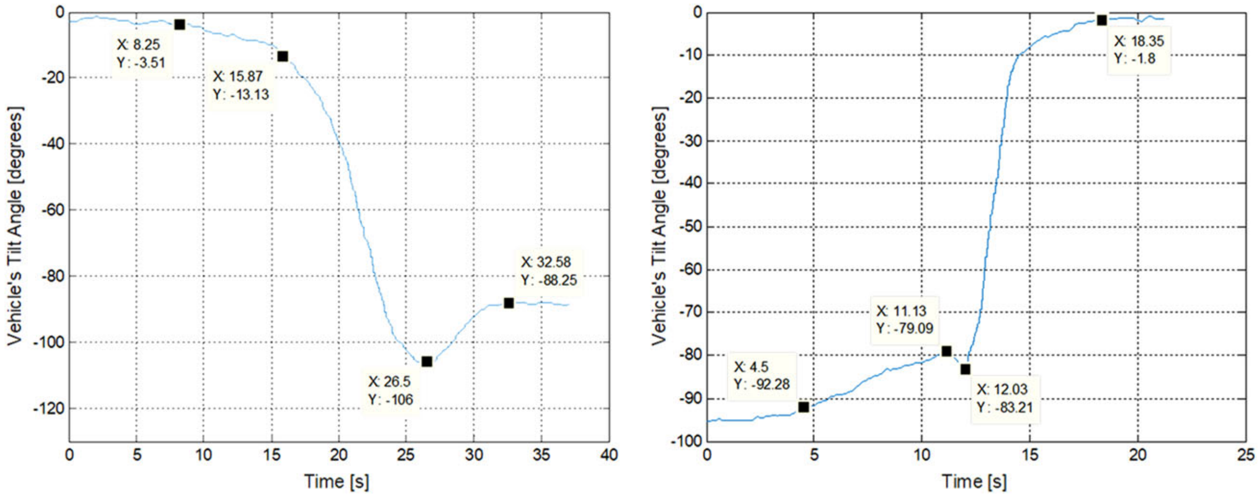

FIGURE 17 The Loon Copter air–water transition (left) and water–air transition (right): vehicle's tilt angle in degrees versus time in seconds

completed, the vehicle is buoyant and the four propellers of the drone clear the water, allowing for a clean takeoff.

When the air–water transition complete, the Loon Copter naturally suspend underwater at a required depth using the ballast system. Figure 18 illustrates the vehicle's suspension test results. Subfigures (a), (b), and (c) represent the vehicle's pitch, roll, and yaw angles underwater, respectively. As shown in the subfigures reference pitch, roll, and yaw represent the required angles underwater. The IMU measurements illustrate that there are small differences between the required and the measured angles in a range of $\pm 3°$. Therefore, the ballast system is capable to stabilize the vehicle's attitude angles underwater.

5.2.4 | Loon copter underwater maneuver

While the Loon Copter is underwater, its rotors are perpendicular to the WS. Figure 19 is a block diagram illustrating the control algorithm. Because the ballast system ensures the vehicle's stability, an open loop control algorithm was developed. The inputs of the command mixing blocks are received directly from the RC transmitter without any PD control corrections. The command mixing blocks are for the right and left motors (M_1, M_4, and M_2, M_3, respectively). For instance, to command the vehicle to roll right, the mixing blocks will reduce the rotational speed of M_1 and M_3 and increase that of M_2 and M_4.

The experimental results of the Loon Copter's yaw step response are shown in Figure 20. Depicted in the figure are the vehicle's yaw angle measurements. The vehicle has an overdamped response due to water resistance. As shown in the figure, the rising time is about 2 s with about one degree of steady state error.

6 | FUTURE WORK

The Loon Copter is a successful proof-of-concept vehicle that highlighted multiple possible areas of future work. The range of wireless communication underwater is an obvious challenge. This may be addressed by investigating acoustic or optical communication techniques, or alternatively, by outfitting the drone with sensors such as sonar, magnetometer and pressure sensors, and control algorithms to make it autonomous for inspection of submerse structures, such as petroleum platforms, ship hulls, and gas pipelines. The current shape of the vehicle can be improved as well. The vehicle's airframe is constructed from off-the-shelf components, which added some

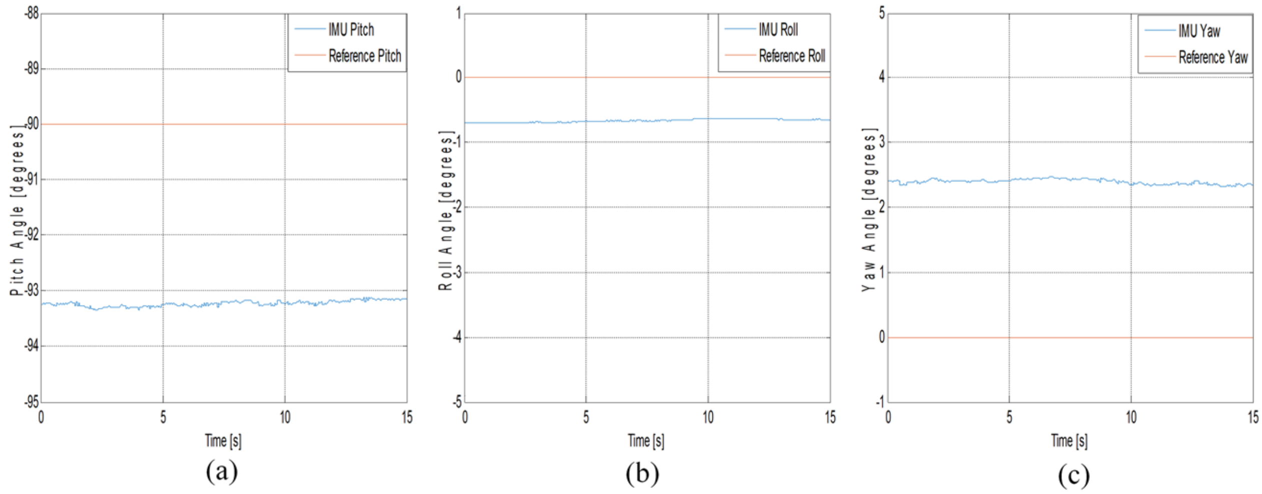

FIGURE 18 Loon Copter's suspension underwater. Subfigures (a), (b), and (c) illustrate the vehicle's pitch, roll, and yaw angles test results, respectively

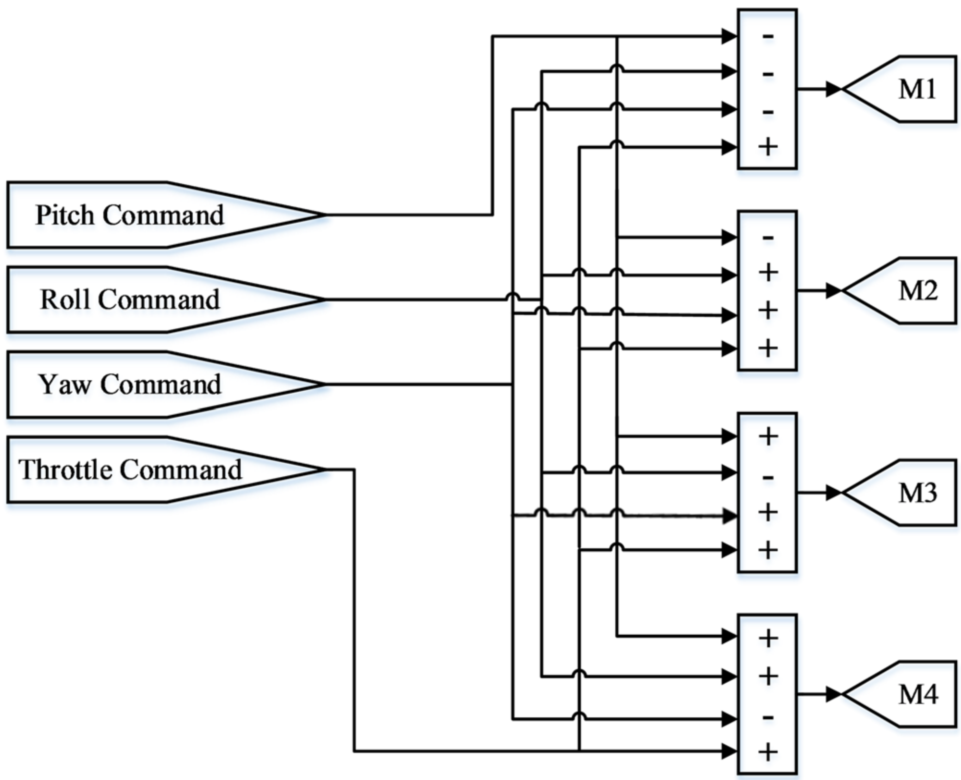

FIGURE 19 Block diagram of aquatic mode control algorithm

penalty to the vehicle's weight, and making the vehicle waterproof increased the surface area of the vehicle and, as a result, increased the vehicle drag. Therefore, there is the opportunity to redesign the vehicle's structure to reduce its weight and drag in air and underwater, which could potentially reduce the vehicle's power consumption and thus increase operation time. As for the control aspect, we will be developing an algorithm to control the depth of the vehicle underwater. This will involve additional pressure sensors and modifications in the software.

Currently, the air–water and water–air transition is operated remotely. A closed loop controller will be required to improve the speed and accuracy of transition. This will require software modifications and additional hardware such as an IMU sensor to keep track of the vehicle's tilt angle. To improve the overall performance of the controller, we are developing a dynamic model to simulate the Loon Copter's aerial and aquatic operation, as well as the transition between air and water. This will include determine the transfer functions of the vehicle's rotors, and the lift and drag coefficients in both media, and the mathematical modeling of the ballast system. As for safety aspect, the Loon Copter needs a failsafe system to prevent the vehicle from sinking in case of water leak or communication loss between the vehicle and the remote.

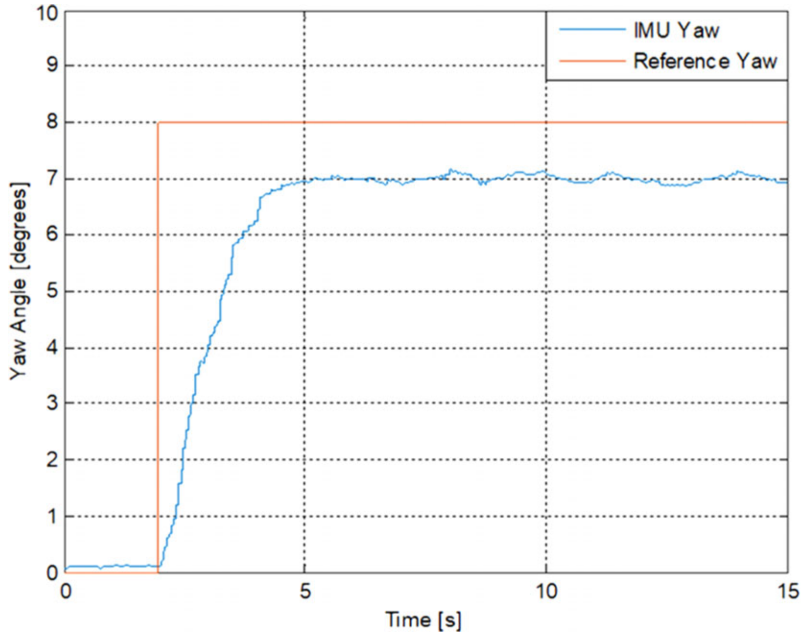

FIGURE 20 Loon Copter's yaw step response underwater

7 | CONCLUSION

This publication explored the design, control, and implementation of our novel hybrid aquatic–aerial quadrotor. The design employs only four brushless DC motors with four counter-rotating fixed pitch propellers. The aerial and underwater maneuver is achieved by manipulating the rotational speeds of the propellers at each rotor. While in aerial mode, the Loon Copter takes flight as a conventional aerial quadcopter and uses four rotors to control the roll, pitch, yaw, and altitude of the drone. While in aquatic mode, the vehicle utilizes the rotors for underwater maneuver and the ballast system for depth control. The Loon Copter achieves a novel seamless air–water and water–air transition using a ballast system. This improves the vehicle's stability underwater and reduces the power consumption. Experimental results demonstrate that the proposed design produced a fully operational prototype with stable flight, operability on a WS, and maneuver capabilities underwater.

ACKNOWLEDGMENTS

The authors would also like to thank Ahmad Kafrouny, Ghassan Abed, and Benjamin Nold for their help in testing the Loon Copter. We also appreciate help from personnel of the Campus Recreation Center at Oakland University.

ORCID

Hamzeh Alzu'bi http://orcid.org/0000-0002-7692-7190

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How to cite this article: Alzu'bi H, Mansour I, Rawashdeh O. Loon Copter: Implementation of a hybrid unmanned aquatic–aerial quadcopter with active buoyancy control. *J Field Robotics*. 2018;35:764–778. https://doi.org/10.1002/rob.21777