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Design and Development a Bimodal Unmanned System

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The objective of this research is to design and build a bimodal vehicle which can operate in both air and water. The design incorporates a variable sweep wing configuration and a compressed gas thruster to clear the water surface. The wing can be folded back 65° to achieve low drag for underwater cruise and a high aspect ratio for long endurance airborne. A compressed gas thruster was designed using off-the-shelf CO_2 cartridges which presses water from chamber to generate thrust that clears the vehicle from the water surface into the air. The hybrid propulsion system with a foldable-blade propeller was developed for the operation in both fluids. This paper covers the experimental test results for the propulsion system with a special designed gear transmission system.

I. Nomenclature

T	=	Thrust
D	=	Drag
W	=	Weight
g	=	Acceleration due to gravity
$\dot{m}$	=	Mass flow rate
A_e	=	Exit area of the water chamber
V_e	=	Exit velocity
p_e	=	Exit pressure
p_0	=	Free stream pressure
SLM	=	Selective Laser Melting
RPM	=	Revolutions per minute
B2UAS	=	Bi-modal Unmanned underwater/air system
PWM	=	Pulse Width Modulation
ESC	=	Electronic speed control
UAV	=	Unmanned aerial vehicle
A	=	Aspect ratio
e	=	Oswald efficient
C_{f_e}	=	Equivalent skin friction
S_{wet}	=	Wetted area
S_{ref}	=	Reference area
C_{D_0}	=	Zero lift drag coefficient

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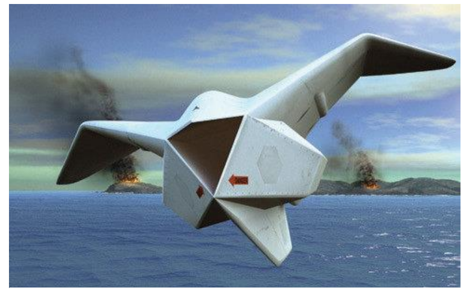
II. Introduction

A. Novel Solution for a Bimodal Unmanned Vehicle

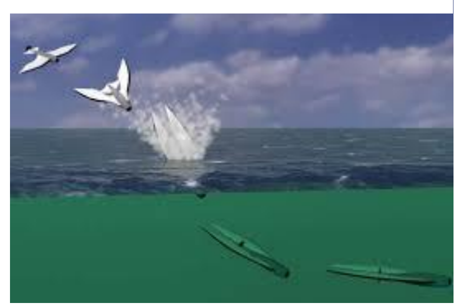
In recent years, an unmanned vehicle that can operate in both air and water has received increasing interest. This multi-functional vehicle can be used for environmental monitoring, disaster management and military surveillance [1]. There are several design concepts under development and some enabling technologies, such as launching from the water or diving into water, have been verified [2]. Some examples are shown in Fig. 1.

In 2005, Lockheed-Martin developed the cormorant UAV [3], a submersible unmanned vehicle a morphing wing structure. This vehicle would be launched from a submarine missile tube using a rocket booster. The Hybrid Aerial Underwater Vehicle developed by the MIT Lincoln Laboratory team has a novel strategy for operating in both air and water [4]. In the water landing process, the vehicle imitates the gannet birds that dive into water to prey fish. The wing can be folded for easy water ingress during the dive. A special nose cone design reduces water impact up to speeds of 7 m/s. In 2011, a biomimetic robotic flying fish was proposed by A. Gao and A.H. Techet. The concept of this aerial-aquatic robot is that it can swim underwater and glide in the air, like a flying fish [5]. In 2014, Beihang University built a submersible unmanned flying boat [6]. It lands and takes off from the water surface as a normal seaplane. When the vehicle needs to dive under water, it uses a buoyancy control system, called water volume regulation system, to submerge and folds back its wing to increase underwater maneuverability. In the 2016, R. Siddall et. al. developed a morphing wing aircraft which can dive into the water [7]. The main wing can rotate around the pivot from 0^o to 90^o driven by a gear and servo. Change of configuration is inevitable for bimodal vehicles, if good performance is required in both fluids. In addition, design trade-offs are needed for operation in water and air.

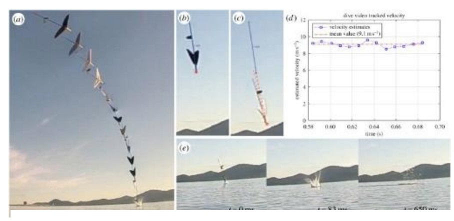
The proposed bi-modal vehicle uses a compressed gas jet propulsion system to rapidly exit the water clear the waves quickly. Since the physical properties of air and water are different, the aerodynamic configuration of an air flight vehicle may not be suitable for operation under water [8]. Similar for the propulsion system, which will be different for both media. These compromises have the be achieved with minimum weight, complexity and cost.



Lockheed-Martin Cormorant



MIT Hybrid Aerial Underwater Vehicle



Imperial College *AquaMAV*

Fig. 1 Examples of bi-modal air vehicles.

B. Propulsion system development

According Malhotra (2016), the CO_2 cartridge can provide sufficient thrust to assist the vehicle transition from water to air. To increase thrust, a water chamber was added to the system to produce more mass flow.

A propulsion system which could operate in both air and water was developed by Y.H. Tan, R. Siddall, and M. Kovac (2017) that uses a gearbox to achieve velocity reduction and torque increase by changing the rotation direction of the motor [9]. The system is compact and only one propeller, optimized for operating in both water and air, is used. The experimental results for this system are very promising. The propulsion system prototype works well in the suitable speed in both fluids. In 2012, R.J. Lock, R. Vaidyanathan and S.C. Burgess designed and tested a flapping foil for propulsion to enable aerial and aquatic motion of a robotic vehicle [10]. However, a propeller design is more feasible for long endurance flight.

Due to the difference of physical properties of air and water, propellers used in aircraft and propellers used in submarines are different. To equip the vehicle with both a water propeller and air propeller, one could use two motors to drive two different propellers. This solution is inefficient since it comes with significant weight penalties. The proposed solution is a hybrid propeller, which is suitable both for air and water. This propeller can save weight and can simplify the power system as only one motor is required.

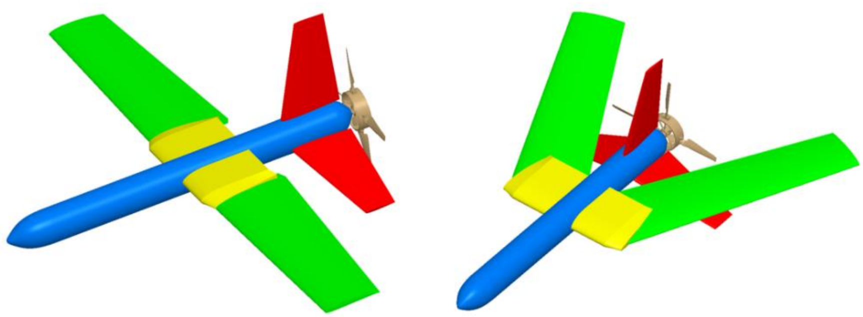
III. Vehicle conceptual design

A. Conceptual design

The current vehicle is a technology demonstrator and has not been optimized for a particular mission. For the convenience of the testing and experiment, the target weight of the vehicle is 3 kg. This technology demonstrator must have the performance capability shown in Fig. 2. The conceptual design approach follows the book of Anderson, Raymer and submarine design. A lot of compromise was made to increase the adaptability in both air and water. The sizing of the wing is determined based on the mission requirements. The sized main parameters are wind loading, aspect ratio, and lift and drag coefficient.

The result of the conceptual design based on the requirement is shown in Fig. 2. The vehicle has a conventional layout during the flight. The wing will be stowed back for 65 deg for the underwater cruise. An inverted Y tail is adopted to avoid interference with the stowed wing and it also widely used on both aircraft and submarine. The high lift coefficient with thin profile airfoil s7075 was used to minimize the volume the vehicle which may create the problem of the buoyancy control.

Parameter	Value
Weight	3.2 kg
Wing area	0.238 m^2
Fuselage length	0.831 m
Wing dihedral	0 deg
Tail anhedral	25 deg
Aspect ratio	9.27
Wing span	1.485 m
Airfoil	s7075
Flight ceiling	400 m
Air speed	20 m/s
Water speed	2 m/s
Stall speed	14 m/s
Mass	3 kg



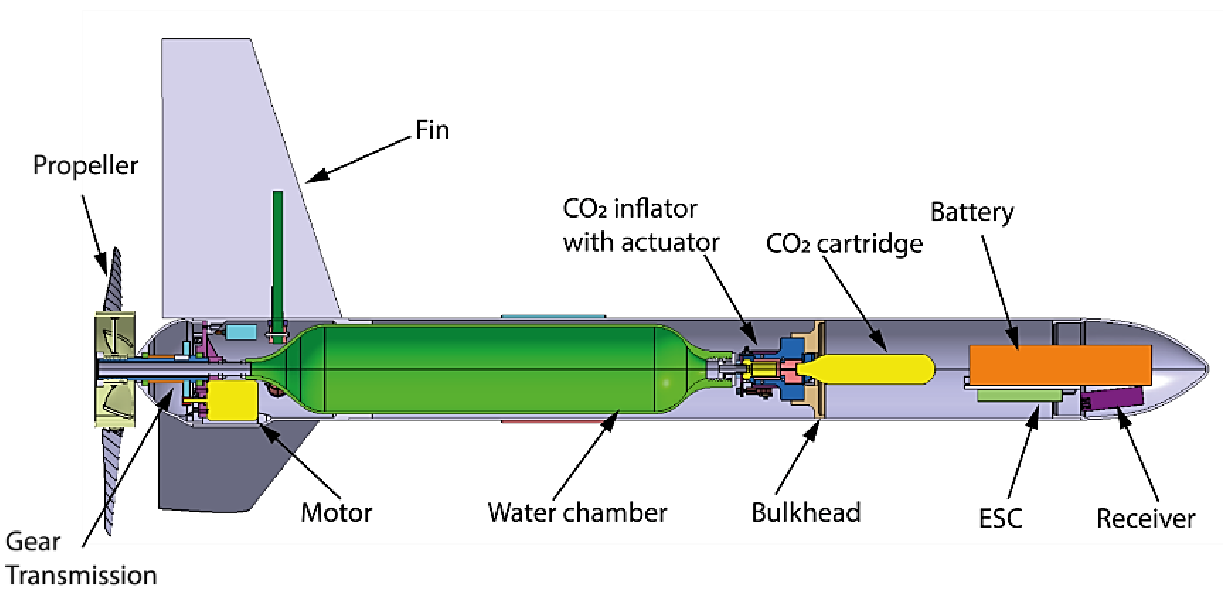


Fig. 2 Bi-modal vehicle design parameters.

B. Thrust to weight ratio

The following thrust to weight ratio was evaluated for the further propulsion system design.

$$\frac{T}{W} = \frac{qC_{D_0}}{W/S_{ref}} + \frac{W}{S_{ref}}\left(\frac{1}{q\pi Ae}\right) \tag{1}$$

$$q = \frac{1}{2}\rho V_{Cruise}{}^{2} \tag{2}$$

$$C_{D_0} = C_{f_e}\frac{S_{wet}}{S_{ref}} \tag{3}$$

where the ratio is evaluated at cruise speed. The value skin coefficient C_{f_e} is evaluated according to [].

$$\frac{T}{W} = 0.3410 \tag{4}$$

The result shows the thrust should be approximately 9.5 N for the current weight.

IV. Hybrid Propulsion System

A. CO_2 thruster for water to air transition

A thruster powered by a standard CO_2 cartridge expels water from a chamber. The thrust generated is according to the rocket thrust equation (5):

$$T = \dot{m}V_e + (p_e - p_0)A_e \tag{5}$$

The design of the thruster and activation system is shown in Fig 3:

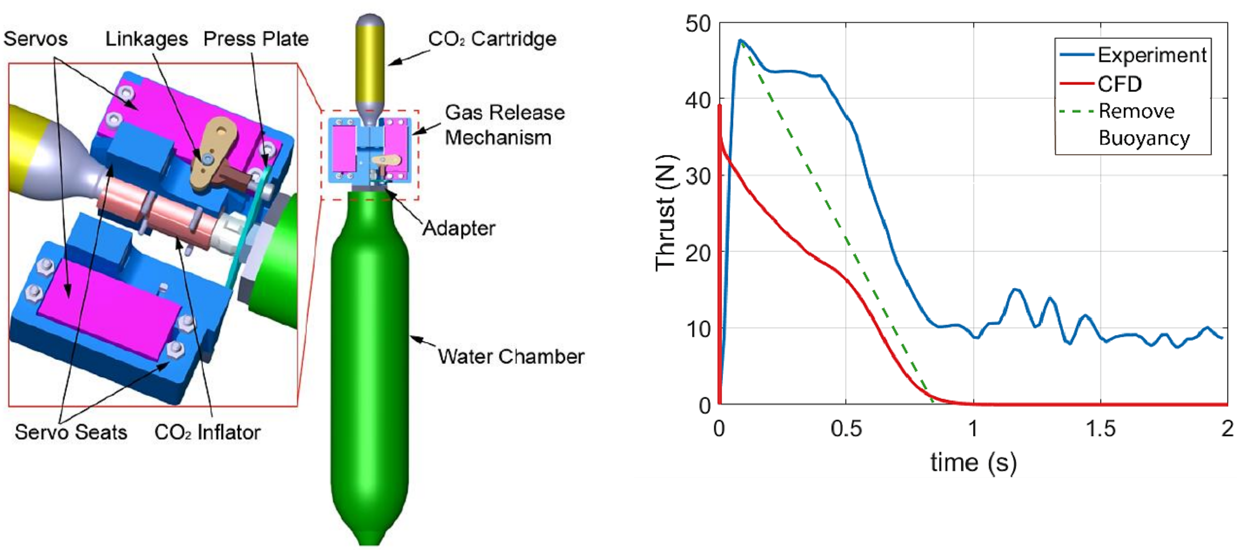


Fig. 3 Layout and performance of the compressed gas thruster.

The thrust is mainly depended on the exit area of the water chamber and the duration of the thrust is depend on the volume of water. CFD analysis and experiments results showed with a 9 mm diameter exit area 47.6N thrust can be generated over 1 s period which is sufficient to lift the vehicle from the water [11]. Further development will be done to evaluate the size and power of the thruster to increase its capability for effective transition.

B. Foldable propeller design

A hybrid propeller is integrated in the overall propulsive system to be able to generate enough thrust in both environments during the mission. In this paper only general data and characteristics will be shown since the vehicle is still in testing phase. For the design of the propeller, an open-source software, called JavaProp was used. A parametric study was done to optimise the propeller for both mediums with the inner propeller optimised for underwater motion and the outer propeller designed for flight.

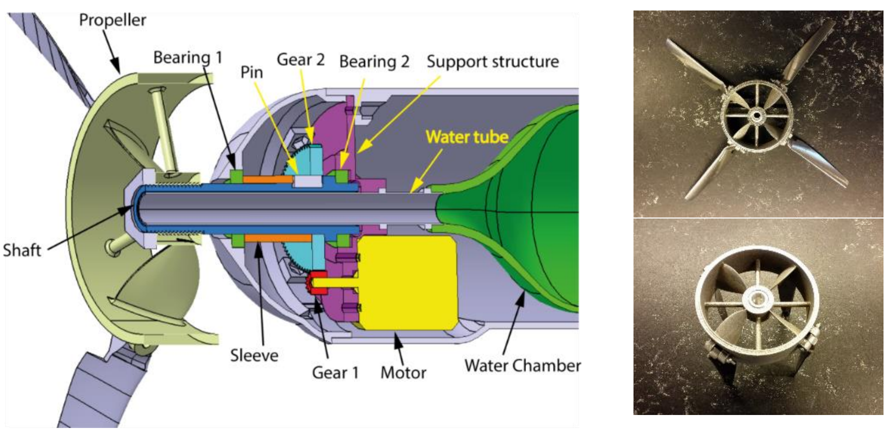
The inputs for the design process are taken from previous design, for similar applications, and from previous research as diameter, RPM for air and for water, target thrust. A parametric investigation was done to choose the number of blades and the local angle of attack to obtain and overall efficiency higher than 65% for both air and water, generating an amount of thrust as much as possible near the target ones.

As an intermediate step, before propeller manufacturing and testing, structural finite element analysis was conducted to be sure that the component can carry the loads on the blades at the target RPM in both air and water. This analysis was used, not only to choose the best material, but also to identify the lower rim thickness to decrease unbalanced masses and at same time resulting in low deformations and stresses.

The prototype was manufactured using additive technology through SLM technique in titanium, to make the component sufficiently strong for underwater tests. For experimental tests the RC Benchmark thrust rig was used to evaluate performance, i.c. thrust, torque, power and vibrations, as a function of RPM.

C. Propulsion system layout

Since the propulsion system is integrated with the thruster a hollow propeller shaft is used rotating around a stationary tube for water exit. Since the tube in the central axis occupied the place for the motor directly driving the propeller, a gear transmission system with the offset motor was developed, as shown in Fig. 4.



Number of blades	4
Pitch angle	5°
Thrust in water	10 N
Thrust in air	15 N
RPM in water	300
RPM in air	6000
Module of gear	0.5
Teeth gear 1	14
Teeth gear 2	84
Shafts distance	24.5
Transmission ratio	6

Fig. 4 Layout of motor and gear transmission system.

D. Gear transmission system design

The layout of the propulsion system produces a design constraint for the transmission system. The gear on the main shaft must be big enough to offset the motor, thus reduction gears were used. A high rotation speed motor with slim configuration was used. The inner diameter of the hollow shaft is 10.5 mm with enough space for the 9 mm water tube. The gear transmission design is constrained by the dimension of the fuselage and the diameter of the tube of the CO_2 thruster. The distance between shaft of the propeller and motor is estimated $d_s = 25$ mm based on the general size of the motors. The pinion (gear 1) on the motor shaft is 14T pinion which is widely used in model helicopters. Two spur gears were used for the transmission. The material of the pinion is aluminium and gear 2 is nylon which can provide self-lubrication and low noise. The parameter of the gear transmission system is shown in Fig. 4.

The motor selected was a Scorpion HK-2520 motor. The value of kv which refers to the constant velocity of the motor is 3500, and power is 770w. The battery for the motor is a 14.8V lipo battery. Under 14.8V voltage, the rpm, which is kv times the voltage, is 51,800. The rpm of the propeller, which is the rpm value of the motor times the transmission ratio, is 8633.

V. Propulsion system testing

The experimental setup for the evaluation of the propulsion system consisted of a test rig, load cell, data acquisition system, 14.8V DC power supply and RPM measurement and control system. The RC bench mark* is used as the RPM measurement and control system. It provides the PWM signal for the ESC to control the RPM of the motor and receives feedback from the motor to calculation the real-time RPM.

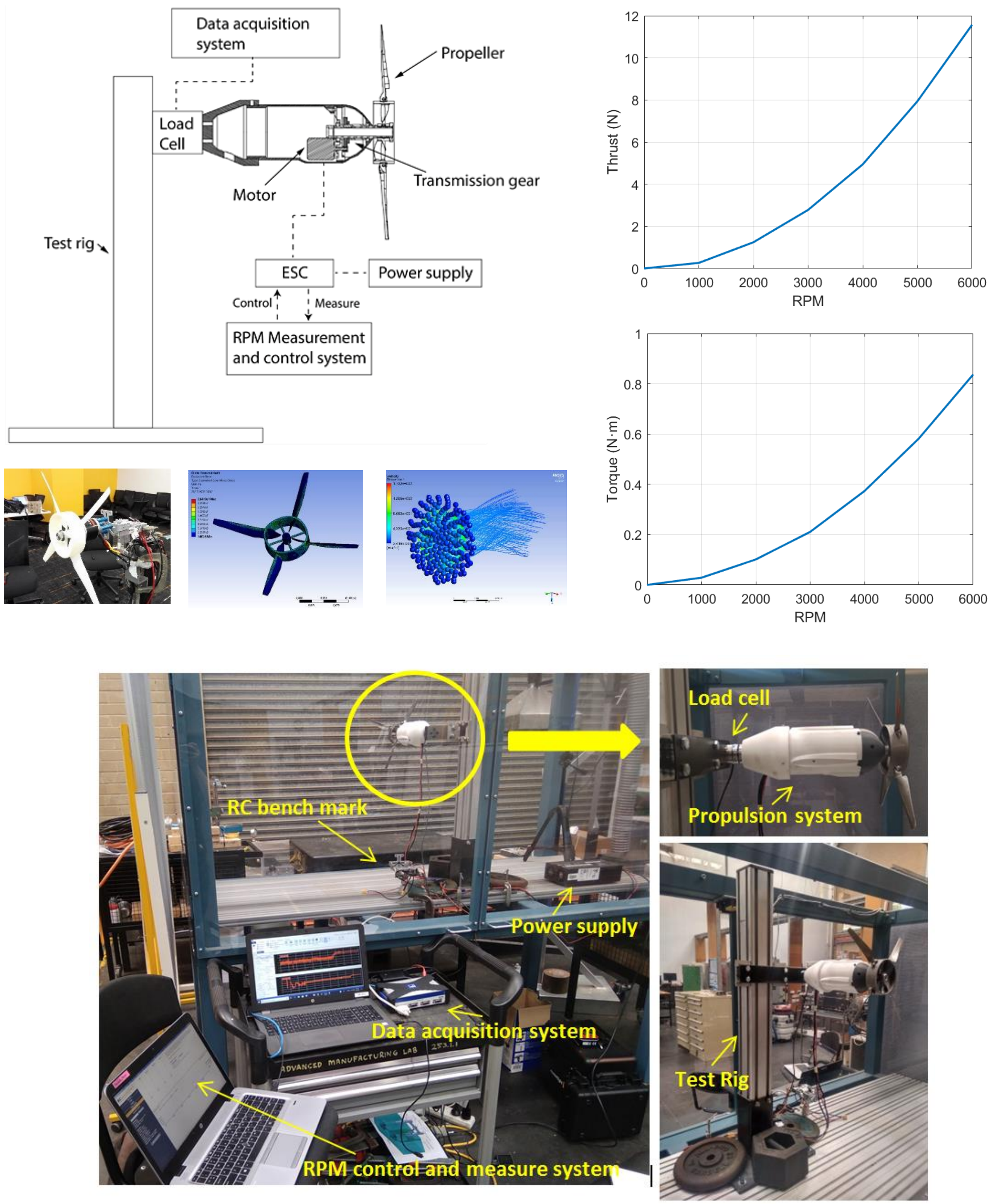


Fig. 5 Experiment setup and results.

As shown in the Fig. 5, the experiment was conducted in the transparent cabinet for safety reason. The propulsion system is fixed on the load cell by screws rigidly. The test rig is built as rigid enough and weights are placed on the bottom of test rig to reduce any possible movement.

HBM* U93 force transducer was used for the thrust load cell. It can measure the tensile and compressive force which is the thrust in this experiment. The nominal force of the transducer is 1 kN. The torque is measured by the torque sensor on the RC bench mark using the same setup. The signal from the force transducer goes through the HBM MX440A universal amplifier and is sent to a laptop where it is captured by the software. The data is exported for analysis. 100 samples were taken for each RPM. The data were processed and the average values for each RPM were obtained.

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VI. Conclusion

A novel configuration and propulsion system were developed for a bi-modal unmanned air vehicle. The vehicle can be useful in both military and civilian mission, eg. surveillance, monitoring and detection. The design is a variable swept wing concept with an integrated propulsion system that consist of a compressed gas thruster to water egress and a hybrid propeller for propulsion in water and air. The hybrid propulsion system includes a foldable outer propeller (air) and a fixed inner propeller (water). This paper presented an overview of the propulsion system design and some experimental results. The results show that the propulsion system delivers the thrust required for all parts of the mission. In future development the vehicle will be optimized for minimum weight by improved compacting and material. The next development phase is stability and control for both underwater and in air. The dive maneuver also needs to be considered for water impact force.

References

[1] Low, K. H., Tianjiang Hu, Samer Mohammed, James Tangorra, and Mirko Kovac., "Perspectives on biologically inspired hybrid and multi-modal locomotion," *Bioinspiration & biomimetics*, Vol 10, No. 2, 2015: 020301.

[2] Yang, X., Wang, T., Liang, J., Yao, G., & Zhao, W., "Submersible unmanned aerial vehicle concept design study," *Aviation Technology, Integration, and Operations Conference*, 2013, pp. 4422.

[3] Graham, W. 2006. Cormorant achieves splashdown. London.

[4] Fabian, A., Feng, Y., Swartz, E., Thurmer, D. and Wang, R., 2012, Hybrid aerial underwater vehicle (MIT Lincoln Lab).

[5] Gao, A. and Techet, A. H., "Design considerations for a robotic flying fish," *OCEANS 2011*, 2011, IEEE, pp.1-8.

[6] Yao, G., Liang, J., Wang, T., Yang, X., Liu, M. and Zhang, Y., "Submersible unmanned flying boat: Design and experiment. Robotics and Biomimetics (ROBIO)," *2014 IEEE International Conference*, 2014, IEEE, pp1308-1313

[7] Siddall, R., Ancel, A. O. and Kovač, M., "Wind and water tunnel testing of a morphing aquatic micro air vehicle," *Interface Focus*, 2017, 7, 20160085.

[8] Yang, X., Wang, T., Liang, J., Yao, G. and Liu, M., "Survey on the novel hybrid aquatic–aerial amphibious aircraft: Aquatic unmanned aerial vehicle (AquaUAV)," *Progress in Aerospace Sciences*, 74, 2015, pp.131-151.

[9] Tan, Y. H., Siddall, R. and Kovac, M. 2017., " Efficient Aerial–Aquatic Locomotion With a Single Propulsion System," *Robotics and Automation Letters*, IEEE , 2, 1304-1311.

[10] Lock, R. J., Vaidyanathan, R., Burgess, S. C. and Loveless, J., "Development of a biologically inspired multi-modal wing model for aerial-aquatic robotic vehicles through empirical and numerical modelling of the common guillemot," Uria aalge, *Bioinspiration & biomimetics*, 2010, 5, 046001.

[11] Guo, D., Bacciaglia, A., Ceruti, A., Marzocca, P. and Bil, C., "Design and Development of a Transition Propulsion System for Bimodal Unmanned Vehicles," *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2018, June, IEEE, pp. 549-558.