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Design, Fabrication, and Testing of Fixed-Wing Air-and-Underwater Drone

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Drone technology has evolved rapidly over the last few decades. Some drones fly while others operate underwater. However, there has not been an effective fixed-wing vehicle that can operate between the two environments interchangeably. The purpose of this project is to design, build, and test a prototype that can achieve these goals.

This paper presents our high-wing, inverted conventional tail drone with a mass of approximately two kilograms. For the atmospheric flight, a propeller mounted on the nose was used (in a puller configuration); for the underwater operation, a propeller mounted on the rear end of the fuselage was used (in a pusher configuration). The batteries and other electronic components were enclosed in a waterproofed casing, while the balsa wood used in structural reinforcements was surface-treated to avoid water absorption. The total volume and mass were controlled as to achieve the neutral buoyancy when submerged under water.

This paper also presents our analyses on aerodynamics and hydrodynamics, vehicle performance in air and underwater, propulsion and power, structure and materials, and the overall strategies to integrate multidisciplinary objectives and constraints into a coherent design. To verify our theory we conducted prototype testing for the air flight, underwater operation, and transition between the two environments. Our air-flight test confirmed that our vehicle was airworthy: it successfully took-off, climbed altitude, and achieved the cruising condition. Our underwater test confirmed that our vehicle was near neutral-buoyancy and that all control surfaces were functional at least when the vehicle was near the water's surface. Additionally, vertical take-off was tested as a water-to-air transition.

Drones that would be able to fly and swim would perform missions that are not yet possible. In recent years, a few prototype experiments have been made using quadcopter designs. Our study represents important milestones towards a fixed-wing approach in which the design demonstrates the potential to carry more payloads and fly longer distances.

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Nomenclature

A	= Area
AR	= Aspect Ratio
b	= wing span
C_D	= drag coefficient
$C_{D,O}$	= initial drag
C_L	= lift coefficient
c	= chord
e	= Oswald's Efficiency factor
k	= induced drag correction factor
m	= mass
S	= wing platform area
T	= thrust
V	= velocity
W	= weight
ρ	= density

I. Introduction

Throughout the years of its development, drones have proven to have a significant impact on surveillance and defense purposes as well as being a scientifically engaging instrument. Underwater vehicles have also proven to have significant impact on the scientific community, both monitoring waterways and exploring depths that have not yet been reached. Now, the idea of combining the two to create one machine has had increasing interest and demand by military branches and engineers.

The importance and interest in developing a water-to-air drone has grown tremendously. Its initial need with the navy and other military branches is to improve surveillance and to detect underwater mines. However, the benefits don't end there. It could also be used to monitor pollution in water and air, help with search and rescue missions, detect oil spills, and survey bridges and piers to ensure safety.

Multiple institutions have tried to master a machine that can fly, submerge, and navigate underwater. Few have been able to incorporate all the demands into one drone, however, those who have, have accomplished great milestones in this new area of study.

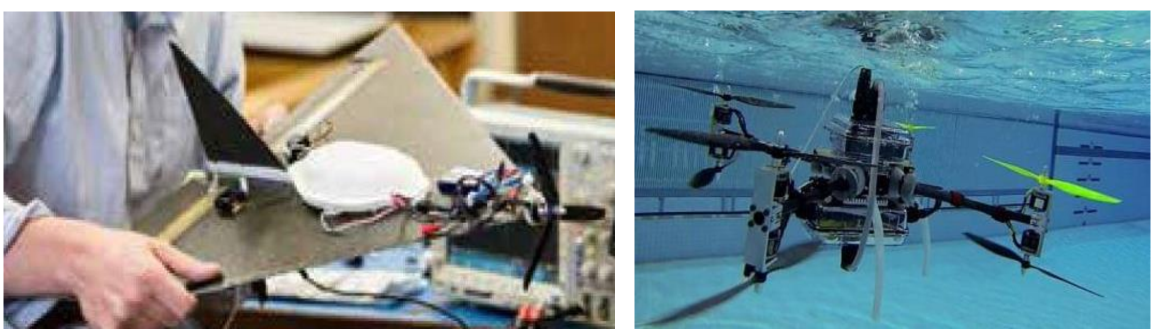

Figure 1: Examples of Hybrid Air/Underwater Vehicle (HUA/UV).

The Applied Physics Laboratory at John Hopkins University was one of the first groups of scientists and engineers to develop a quadcopter that could submerge underwater and then continue to fly once breaking the water's surface. The machine was named CRACUNS[1], Corrosion Resistant Aerial Covert Unmanned Nautical System, and has proven to be a giant stepping-stone in the development of water-to-air drones. It houses a lightweight composite airframe that can withstand the pressure of being underwater, and the components outside of this airframe are safe from corrosion due to commercial coating[1]. CRACUNS has been able to withstand the effects of saltwater and is able to communicate without a tether. However, the areas of improvement involve its movability under water and launching criteria. Although it can reach moderate depths, it must to be launched from a fixed position in the water and is only mobile above the water; therefore, to move to a different location underwater, it must exit the water, relocate, and resubmerge[1].

Rutgers University took on a similar design in which a quadcopter was attached to a tether and could submerge both in and out of the water[2]. Their machine has been able to move freely in both water and air by adjusting the direction and angles of the motors. Its movability under the water is its initial draw; however, the thin wire that permits the controls to penetrate the water is something they hope to improve through acoustics[3].

Oakland University has also demonstrated great strides in the development of water-to-air quadcopter drones. They have successfully performed aerial, water surface, and underwater navigation. For the drone to travel underwater, it rotates the body of the motors to different angles allowing the drone to move forward smoothly in the water. It also follows GPS navigation like a regular air drone and uses a buoyancy chamber to sink into the water. "It is the first multirotor drone capable of filling its buoyancy chamber to sink underwater, tilt 90 degrees and move around beneath the water's surface"[4].

II. Design Objectives and Constraints

The objective of the design, fabrication, and testing of the drone prototype is to provide a fixed-wing drone that has the capabilities like that of quadcopters. The goal is for the drone to be able to take off, perform a figure eight pattern in the air, land on the water, submerge underwater to perform a figure eight pattern again, and then achieve vertical take-off back into the air. In this study, there are no constraints on the payload mass, flight endurance, or submerged depth. The anticipation is that the length of the air figure eight will be such that compared to a football field where as the underwater portion will be at least a quarter of the size.

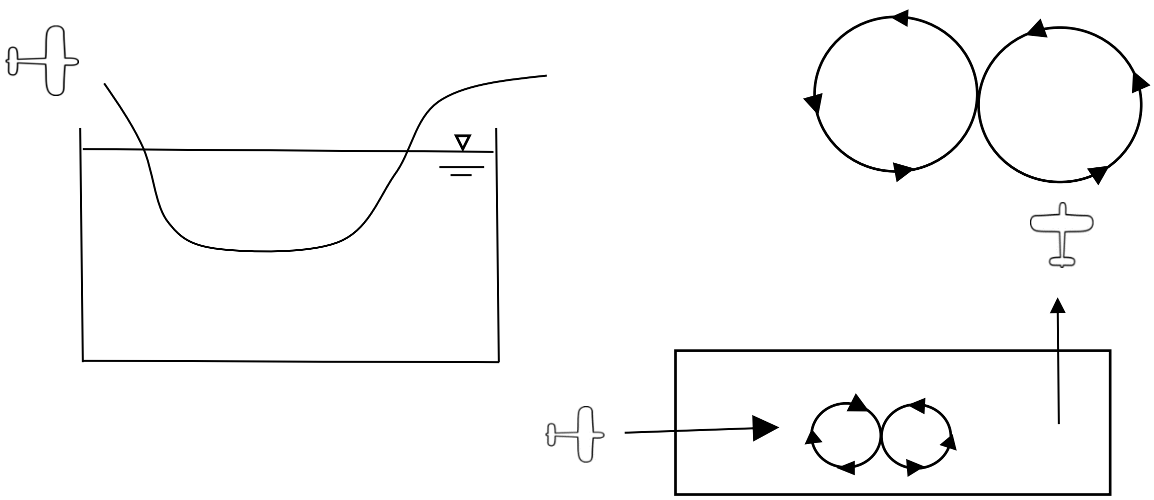

Figure 2: Demonstration of CX-2 performance in and out of water.

III. Selected Configuration

The prototype discussed in this paper is referred to as the "CX-2" (for "Catholic University's Experimental Prototype 2"). The CX-2 (as seen in Figure 3) is a high-wing, inverted conventional tail drone. The rectangular wing structure was chosen because of its simplicity and ability to provide stable lift. The rudder is placed underneath the stabilizer pointing downwards to control mobility under the water. This placement also helps decrease the distance between the center of drag and the center of mass to better align the direction of thrust with the center of mass.

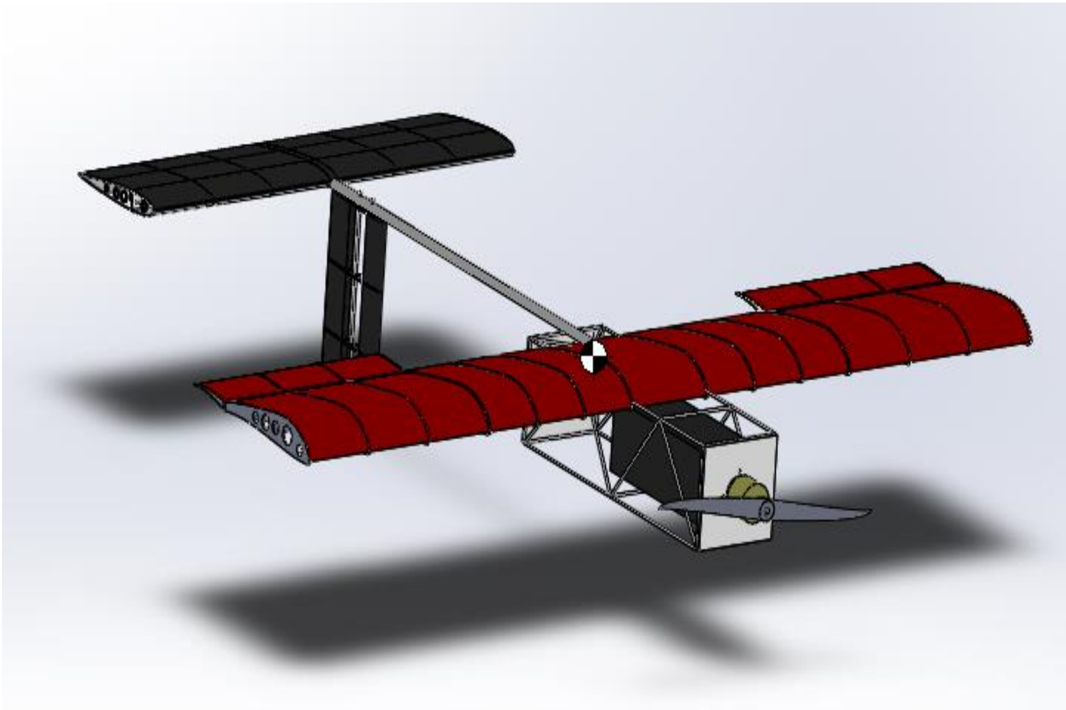

Figure 3: SolidWorks model of the CX-2.

IV. Aerodynamics

The airfoil chosen for the CX-2 wing was the Selig 1223 (Figure 4) based on its ability to provide enough lift at slow speeds. For the stabilizer, the NACA 0012 was chosen for its airfoil shape. Additionally, the tail of the CX-2 was modeled using the free software, XFLR5, to analyze the performance of the chosen airfoils and construction as seen in Figures 4 and 5.

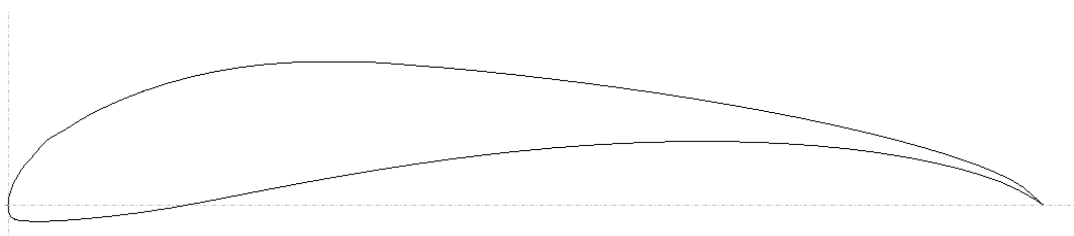

Figure 4: Selig 1223 airfoil design.

The required thrust for a propeller-motor aircraft in cruising condition is minimized when the lift-to-drag ratio, *L/D*, is maximized. A summary of parameter values assumed in our aerodynamic analysis are presented in Table 1.

Table 1: Assumed Parameters in Aerodynamics Analysis

Parameters:	Values:
Mass, *m*	2.00 kg
Wing Platform Area, *S*	0.23 m^2
Chord, *c*	0.23 m
Wing Span, *b*	1.00 m
Aspect Ratio, *AR*	4.35
Oswald's Efficiency Factor, *e*	0.87
Induced drag correction factor, *k*	0.084
Density of air, ρ	1.23 kg/m^3

The lift-to-drag ratio acts as the slope of the line and the line tangent to the curve is the point of maximum lift-to-drag. Based on this analysis, the maximum ratio value was calculated to be 8.62.

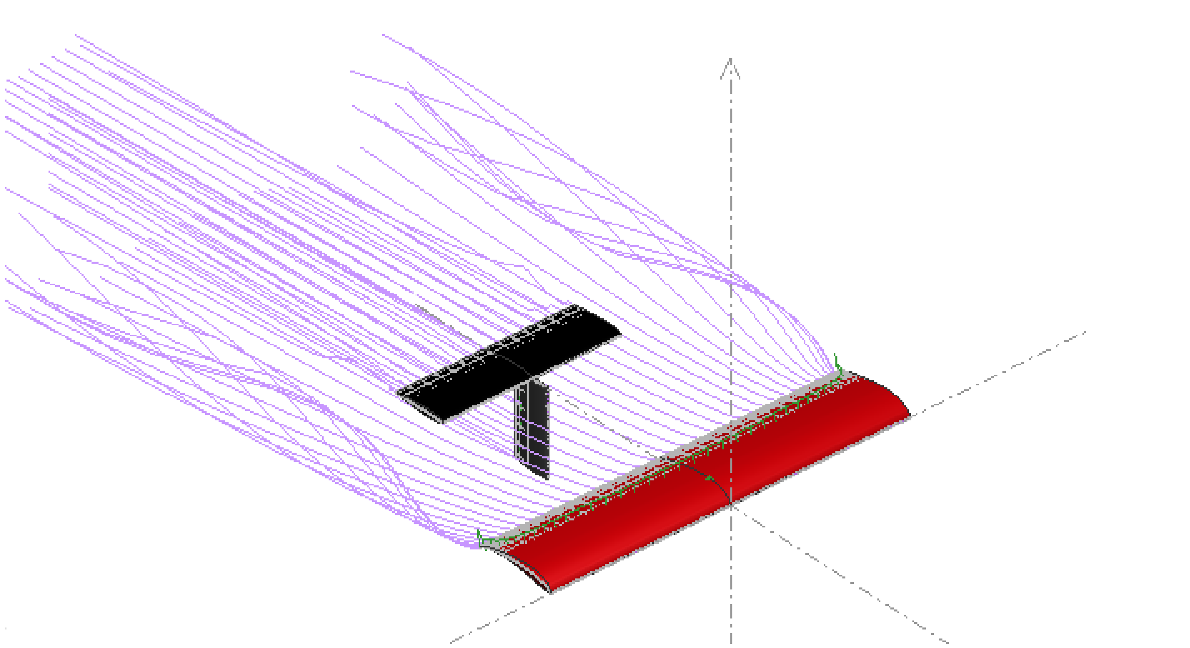

Figure 5: Simulation of CX-2.

Figure 5 shows a screenshot from an aerodynamic flow simulation in XFLR5, which is a free software for evaluating airfoil designs. The software predicted the maximum L/D value of approximately 14, which was much higher than our own prediction of 8.6 that was calculated using the input parameters in Table 1. It is hypothesized that this difference was generated because the simulation could not construct the complex fuselage of the CX-2. Therefore, the initial drag coefficients were different between the two calculations; we used a representative value of 0.04 that is typical for RC planes that are about the size of our drone.

V. Performance

A. Air-to-Water and Water-to-Air Transition

In order for the CX-2 to successfully transition from air to water and from water to air, the drone has to be dense enough to submerse itself in the water, but light enough to fly. Finding the required thrust and buoyancy force is crucial for determining what the minimum mass should be to fulfill these constraints.

Buoyancy can be calculated (Equation 1) using the drone's volume: the volume of water displaced multiplied by the density of water and gravity. This demonstrates that the buoyancy force is equal to the weight of the water displaced. SolidWorks calculated the volume to be 0.001507 m^3. MATLAB was then used to calculate the buoyancy force to be 18.65 N. This means, for the drone to naturally submerge itself underwater, it would need a weight greater than 18.65 N, or a mass greater than 1.96 kg. Therefore, if the tested mass is in fact 2 kg, it should be able to successfully transition from air to water.

$$F_B = \rho g V \tag{1}$$

When returning to the air (Figure 6), the drone needs to produce exactly enough thrust to counter its weight if the lift is not considered. Therefore, the thrust must be at least 19.62 N.

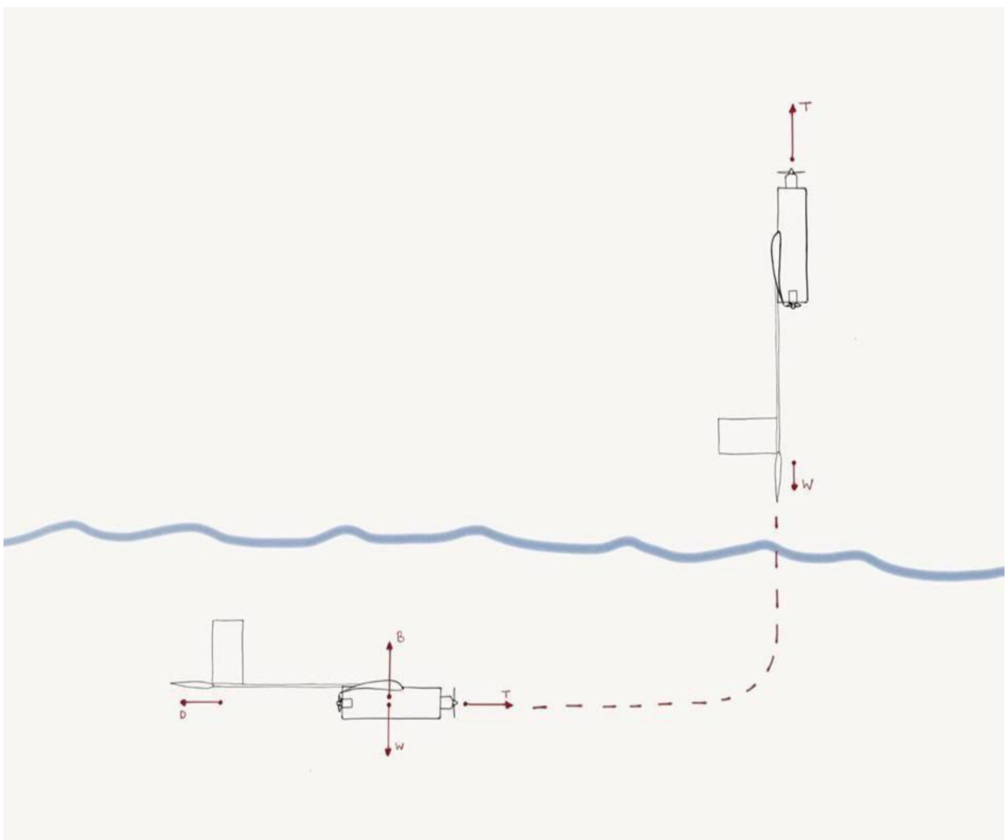

Figure 6: Take-off of the CX-2 from water to air.

B. Vertical Take-Off

With an estimated mass of 2 kg, the drone's weight is equivalent to 19.62 N. The thrust in the air needed to counter this must then be at least equal to this value. However, a thrust-to-weight ratio greater than 1 is more desirable. The motor selected came with specification sheets that said, if it was paired with a 13x4 propeller, it could give a thrust of 50 N. When this was tested, the thrust was measured to be about 30 N. Despite the fact that the thrust was much less than anticipated, a thrust-to-weight ratio of 1.5 was found and is theoretically sufficient for the drone to take-off vertically from the water's surface.

C. Atmospheric Flight: Cruising Conditions

It is known that the drag coefficient, lift coefficient, drag, and thrust will all change with velocity. When velocity is increased, the lift coefficient will decay, and by extension, the drag coefficient will decay as well. The range of velocities and coefficients were carefully selected because it is not possible for either coefficient to exceed 2 and it is unlikely that the drone will reach speeds above 20 m/s; no velocity above this limit should be tested.

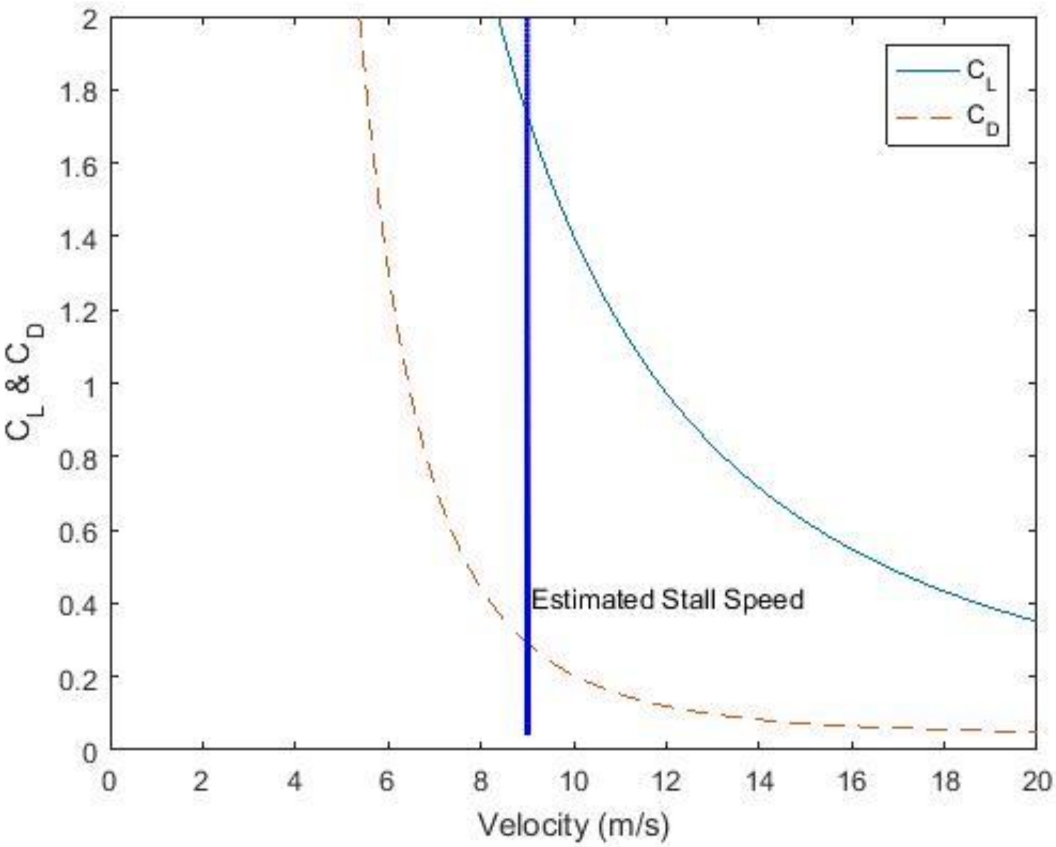

Figure 7: The decay of the drag and lift coefficients over a range of velocities.

The result (Figure 7) shows the drag coefficient originally decaying faster, then leveling off at about 9 m/s where the angle of attack reaches its maximum. This means values for the lift and drag coefficients are invalid for velocities below this line, known as the stall speed. The maximum angle of attack is also an indication that steady level flight will occur at a lower angle of attack, velocity, drag coefficient, and lift coefficient.

By realizing the lift-to-drag ratio is equal to the ratio of the lift coefficient over the drag coefficient, it is possible to calculate at what velocity the maximum lift-to-drag ratio occurs. This is tested at multiple masses to account for any variation in mass the CX-2 might have, even though the measured mass was recorded to be 2 kg. The results (Figure 8) show that the smaller mass reaches its maximum lift-to-drag ratio at a lower velocity. The maximum ratio of the larger mass occurred at a much higher velocity. A smaller mass also proves to have a larger lift-to-drag ratio than a larger mass. The 2 kg mass had a maximum ratio of about 8.64 and occurred at about 14 m/s.

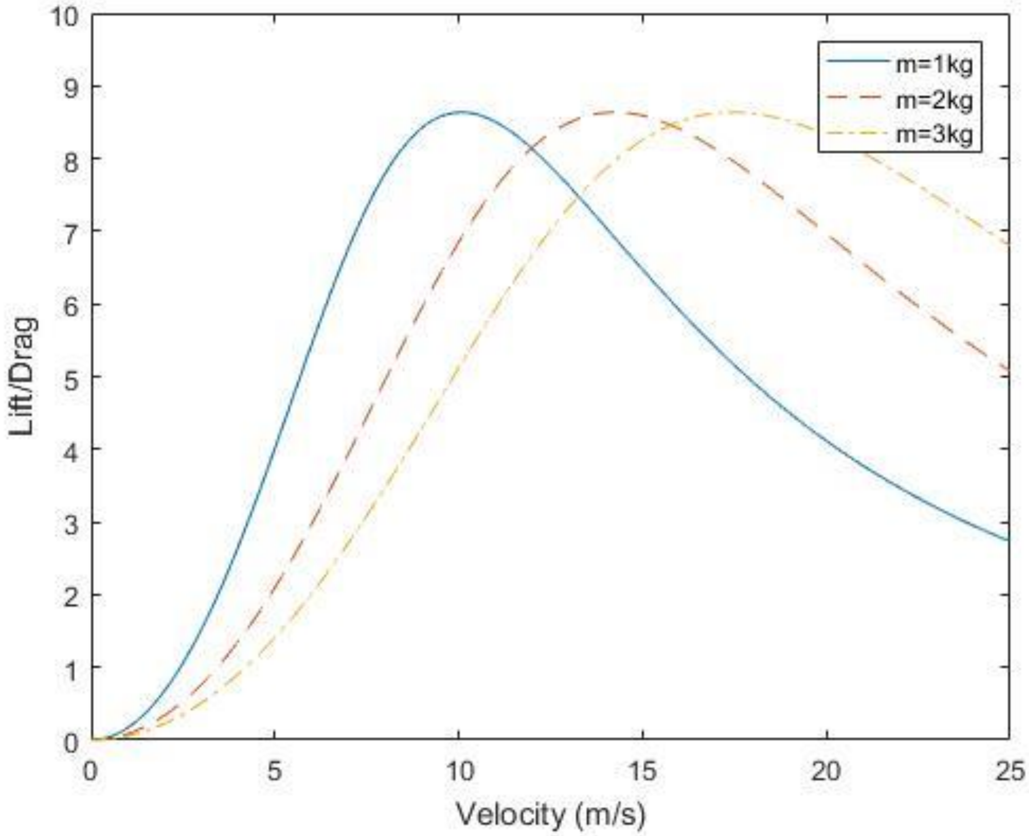

Figure 8: The lift-to-drag ratio of three different weights over a range of velocities.

Because thrust equals drag in steady flight, drag can be used to determine the relationship between velocity and thrust. Drag is made up of two parts: zero-lift drag and the drag from lift. The drag from lift calculates drag using the lift coefficient. Zero-lift drag, on the other hand, uses the zero-lift drag coefficient assigned to the CX-2. Where the two drags intersect is the cruising velocity. Cruising conditions for propeller aircrafts occur when the drag, and, by extension, thrust are minimized.

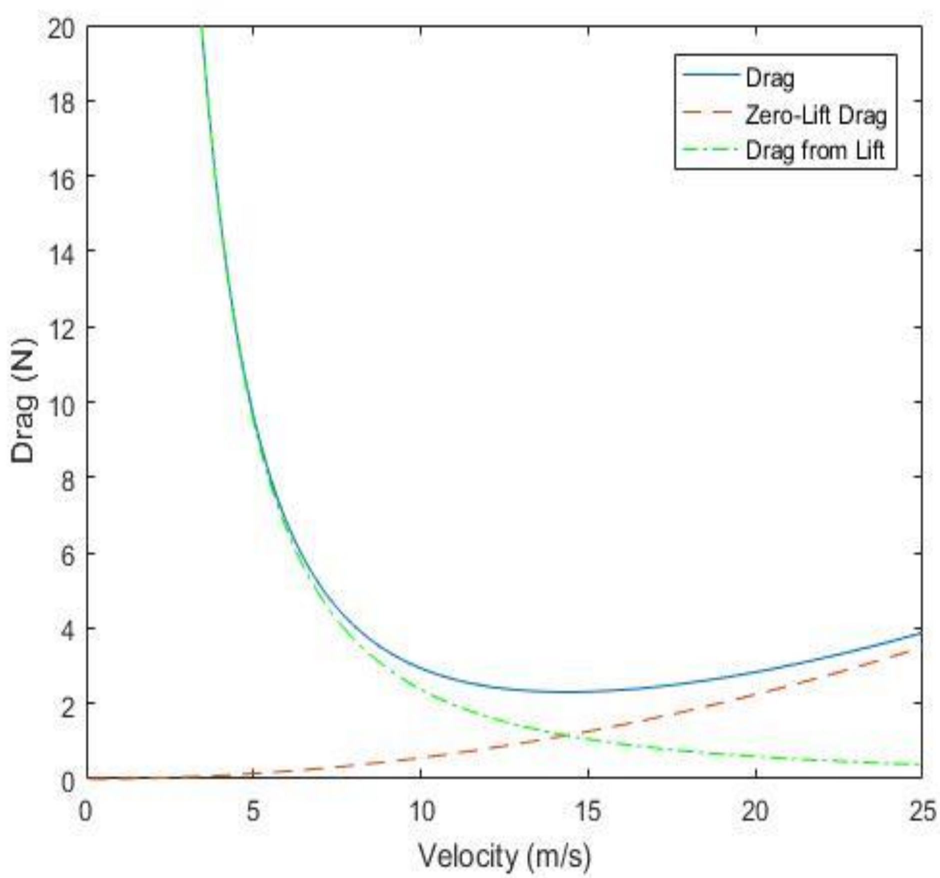

Figure 9: Drag, zero-lift drag, and drag from lift over a range of velocities for in-air flight.

The results of the calculated relationship between the CX-2's drag and velocity in Figure 9 shows that drag initially drops with velocity because, while the velocity was low, the drag coefficient was high and then quickly decreased. The minimum drag, which is equivalent to minimum thrust, is 2.3 N and the corresponding velocity is 14 m/s. After this velocity is reached, the drag and thrust will begin to increase again. Though these theoretical results give a good look at what to expect for thrust, experimentation should still be performed.

D. Underwater Operation

During the underwater portion, the CX-2 drone will behave differently underwater due to the density of water. Lift is negligible for the purposes of underwater operation and will not be in the calculations; therefore, only zero-lift drag will be considered. After looking at the values produced in Figure 10, it was unlikely the drone would go faster than 0.7 m/s (1.5 knots). There is also minimal difference in velocity for thrusts over 2 N.

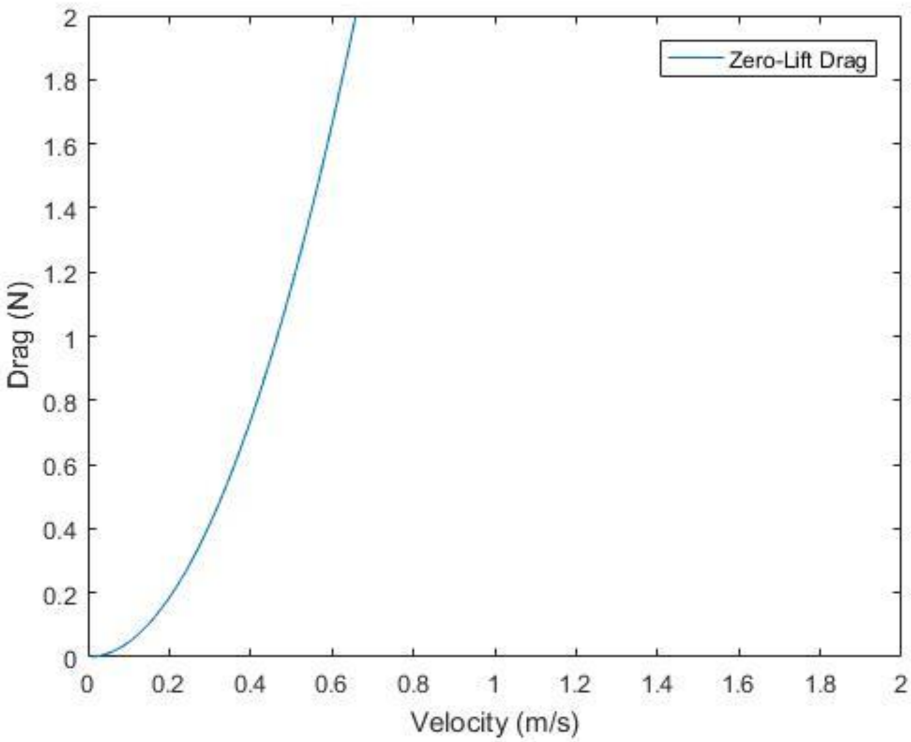

Figure 10: Drag, zero-lift drag, and drag from lift over a range of velocities for underwater flight.

Because it is not predicted to go much above 0.7 m/s, it would take approximately 50 s to complete the figure eight if the path is approximately 35 m. The battery can maintain this velocity for 23 minutes, which means the CX-2 will be able to complete the figure eight underwater at 2 N of thrust.

VI. Structure, Materials, and Fabrication

The CX-2 was built using lightweight materials. The fuselage, wing and rudder spars, and tail were constructed using carbon fiber rods. The motor mounts as well as the wing and tail ribs were made from polycarbonate. A limited amount of balsa wood was wrapped around the ribs to provide a surface that the monokote skin could be applied to.

To prevent the wood from absorbing water while submerged, the balsa wood was treated with POR15. POR15 is a sealant designed to prevent and stop metal from rusting. However, this product can be applied to several other materials including wood, making them waterproof. The POR15 doubled the weight of the balsa wood. The weight of the POR15 treated balsa wood represented 3% of the total weight of the drone.

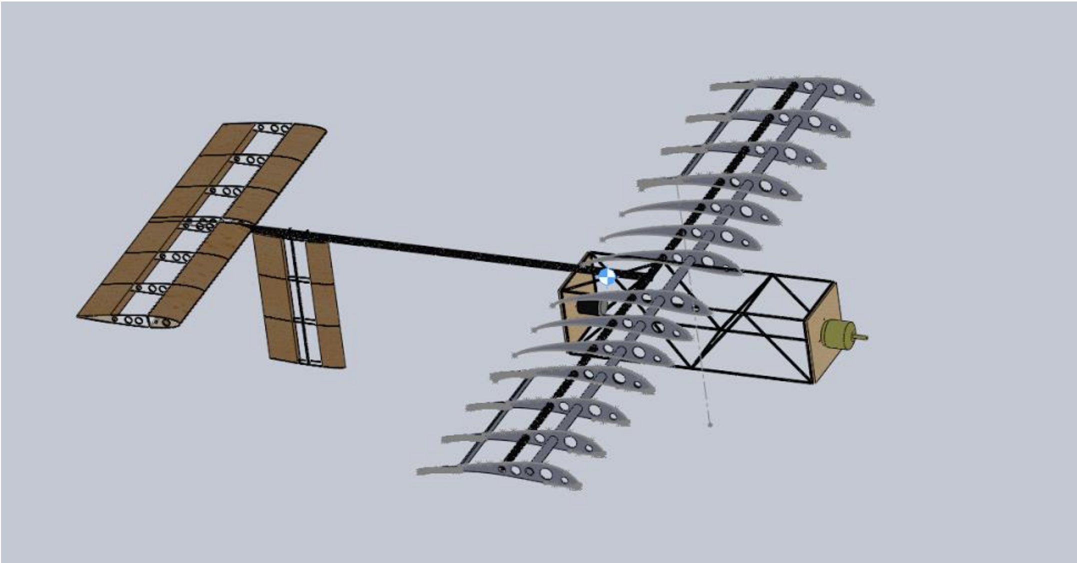

Figure 11: CX-2 3-D model.

The CX-2's electronics were packed into a waterproof container. A water bottle was used for this container (seen below in Figure 12). Holes were cut into the bottle for the wires and they were then sealed using grommets and epoxy.

Figure 12: CX-2 before underwater testing.

VII. Flight Tests

A. Underwater Operation

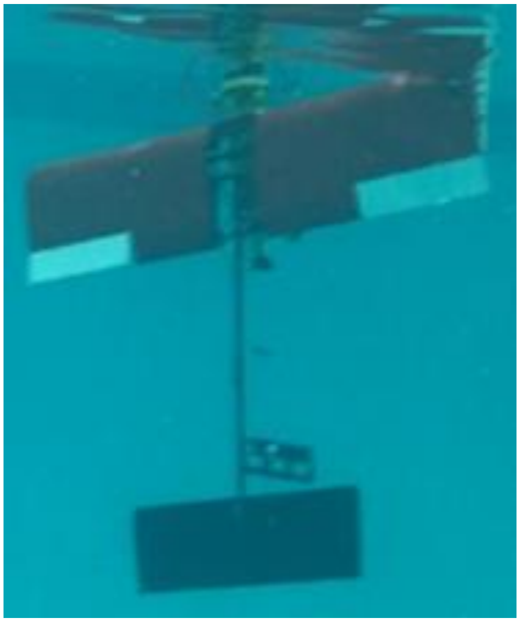

Figure 13: CX-2 underwater before vertical take-off testing.

For underwater operation to be possible, the CX-2 must meet several requirements. The drone should be neutrally buoyant, the electronics and structure need to be waterproofed, and the drone must be able to meet performance standards. The resulting weight of the drone needed to be 1.95 kg to be almost neutrally buoyant and the weight before testing was 1.94 kg, making the drone neutrally buoyant. When the CX-2 was placed underwater, it maintained its position, neither floating up to the surface nor sinking to the bottom.

The waterproofing of the structure and electronics was also successful. The structure did not absorb any water and the electronics container spent thirty minutes submerged underwater. When the electronics were taken out of the container, they were fully functional and did not fail.

However, the drone was not able to operate underwater and further underwater testing with regards to mobility and performing the figure eight could not be done. The CX-2's microcontroller was not able to connect and receive signals while underwater.

B. Vertical Take-off

Figure 14: CX-2 during vertical take-off testing.

The vertical take-off testing was conducted by placing the CX-2 in a pool, positioning it directly below the surface. The drone was placed in a vertical position and the motor was to be put to full power. The goal of the test was for the CX-2 to exit the water and begin flying. The testing was partially successful because the CX-2's main wing was able to clear the water before falling forward into the water. It is hypothesized that this is due to the positively buoyant tail that caused a moment once the main wings breached the water's surface. This is important because the majority of the drone's mass is located at the main wing area.

C. Atmospheric Flight

The flight test was initially comprised of multiple objectives. These objectives included taking off, flying, completing a figure eight, and landing. The goal was that during the flight test the total flight time, the time taken to perform a figure eight, and area needed to perform the figure eight would be measured and calculated.

Figure 15: CX-2 in flight.

On Sunday November 13, 2016, the CX-2 achieved flight on two separate occasions. The first test lasted 23 seconds and ended in a crash landing. The crash was caused by a faulty connection between the motor and the ESC.

The team repaired the damage sustained during the first test and sent the CX-2 out for a second flight. The second flight lasted 26 seconds and ended in a crash landing that left the CX-2 critically damaged. The CX-2 gained a higher altitude than it did in the previous flight. When the pilot began the figure eight pattern, the drone banked left and proceeded to drop into a nosedive. Both wings were severely damaged and the wire frame was in pieces. The tail had been dislocated and hung at an angle when it was originally perpendicular to the wing.

VIII. Conclusion

The CX-2 was designed to be the first fixed-wing drone that would be able to fly both in and out of water. While meeting these criteria, it would perform figure eight patterns in both atmospheres and demonstrate vertical take-off. Based on the analyses and testing, the CX-2 was successful in flight. During the flight test, although it experienced crashes due to disconnections in wires or possible overloading of the electronics, the flight was considered a success because it demonstrated enough lift for take-off. Additionally, for water-to-air transition testing, it exhibited neutral buoyancy within the water. Although the physical testing for vertical take-off was incomplete due to the drone falling to a horizontal position after the main wing breached the surface, it was a milestone in the experimentation and research of the drone. The hopes for future work are to further improve upon these results so that the CX-2 can perform figure eights in both atmospheres and have a successful transition from water to air though vertical take-off.

Acknowledgments

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References

[1]Brown, G., "New UAV Can Launch from Underwater for Aerial Missions." *New UAV Can Launch from Underwater for Aerial Missions.* N.p., n.d. Web. 04 Sept. 2016

[2]Blesch, C., "Navy Funds Rutgers to Develop Drone Equally Adept at Flying and Swimming." *Media Relations.* N.p., n.d. Web. 04 Sept. 2016

[3]Clarke, C., "This Waterproof Quadcopter Is Also a Submarine." *Popular Mechanics*. N.p., 04 Dec. 2015. Web. 04 Sept. 2016.

[4]"OU Team's Underwater Drone Competing for $1M Prize in International Competition." OU Team's Novel Underwater Drone Competing for $1M Prize in International Competition. N.p., 28 Jan 2016. Web. 04 Sept. 2016.

[5]Sadraey, M., "Drag Force and Drag Coefficient." *Aircraft Performance Analysis, VDM Verlag Dr. Muller*. 2009.

[6]Nita, N., and Scholz, D., "Estimating the Oswald Factor." Aero—Aircraft Design and Systems Group (2012). Web. 15 Nov. 2016.

[7]Dioser Ferreira dos Santos,"Prototype Demonstration of Fixed-Wing Drone that Could Fly and Swim", July 2016

[8]Crowe, C. T., and D. F. Elger. *Student Solutions Manual: To Accompany Engineering Fluid Mechanics, 7th Edition*. New York, NY?: Wiley, 2002. Print.

[9]"Shape Effects on Drag." *NASA.* N.p., n.d. Web 04 Apr 2017

[10]"Fluid Mechanics Submarine Design." *Wordpress,* N.p., 14 Oct 2011. Web. 04 Apr 2017

[11]MacDonald, F., "WATCH: What's Causing This Crazy Pool Vortex?" *ScienceAlert.* N.p., n.d. Web. 04 Apr 2017

[12]"Prototype Fish Robot, UPF-2001," *Prototype Fish Robot, UPF-2001.* N.p., n.d. Web. 04 Apr 2017

[13]"Trainer Design," *Trainer Design.* N.p. n.d. Web. 04 Apr 2017

Appendix A: Team Members

Figure A-1: Front Row (Left to Right): Meaghan Rush, Peter Warwick, Caleb Fischer, Danielle Caruccio

Back Row (Left to Right): PJ Smith, Eric Smith, James Carroll, Kevin Motylinski

Appendix B: Aerodynamics

The required thrust for a propeller-motor aircraft in cruising condition is minimized when the lift-to-drag ratio, L/D, is maximized. The lift-to-drag ratio can be calculated by taking the fraction between C_D and C_L:

$$C_L = \frac{L}{2\rho V^2 S} \tag{1}$$

$$C_D = C_{D,o} + kC_L \tag{2}$$

In Equation 2, C_D is the drag coefficient and $C_{D,o}$ represents the initial drag factor, which can often be found specific to the type of wing being used and the overall drag of the craft. In this evaluation, 0.04 was used for the $C_{D,o}$ calculation because it is the typical coefficient found for an RC plane. Additionally, k is the induced drag correction factor and C_L is the lift coefficient factor which can be found using Equation 1. In Equation 1, it can be assumed that L, the lift factor, is equal to the weight of the drone, ρ is the density of the air, V is the velocity, and S is the wing platform area. Below are equations used to calculate the induced drag coefficient:

$$k = \frac{1}{\pi e AR} \tag{4}$$

$$AR = \frac{b^2}{S} \tag{5}$$

$$e = \frac{1}{1.05 + 0.007\pi AR} \tag{6}$$

Here, AR is representative of the aspect ratio, which is inversely proportional to the induced drag correction factor[6]. Furthermore, b is the wingspan and e is known as the Oswald efficiency factor[7], which is expected to be between 0.7 and 0.9, for rectangular wings[6]. A summary of assumed parameter values is presented in Table B-1.

Table B-1: Assumed parameters in Aerodynamics analysis

Parameters:	Values:
Mass, m	2.00 kg
Wing Platform Area, S	0.23 m^2
Chord, c	0.23 m
Wing Span, b	1.00 m
Aspect Ratio, AR	4.35
Oswald's Efficiency Factor, e	0.87
Induced drag correction factor, k	0.084
Density of air, ρ	1.23 kg/m^3

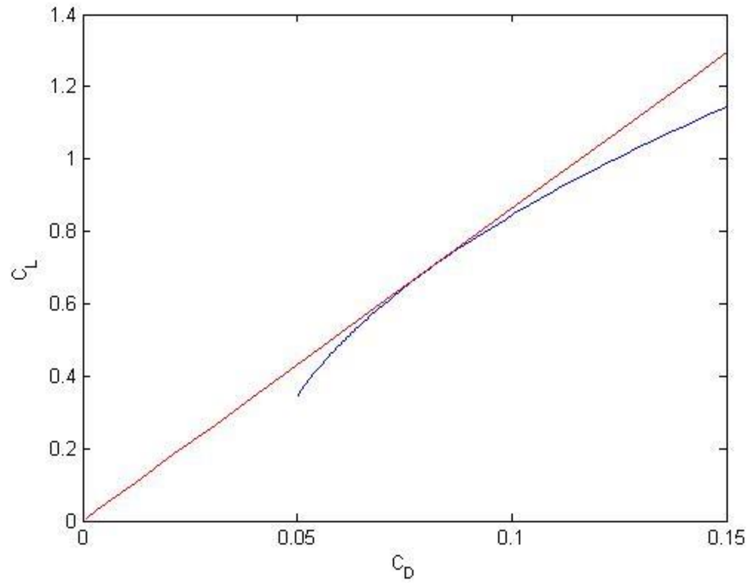

Figure B-1: Drag Polar Graph

Figure B-1 is the drag polar for the CX-2, assuming the parameters summarized in Table B-1. The lift-to-drag ratio acts as the slope of the line and the line tangent to the curve is the point of maximum lift-to-drag. Based on this analysis, the maximum ratio value was found to be 8.62.