Research Project in Mechatronics Engineering

Type of Report

On the Feasibility of a Robotic Seaplane with 3D Printed Wings

Otto Walker

Project Report ME003-2024

Co-worker: Isara Nua

Supervisor: Dr Liarokapis

13 October 2024

UNIVERSITY OF AUCKLAND
Waipapa Taumata Rau
NEW ZEALAND

ENGINEERING
DEPARTMENT OF MECHANICAL AND MECHATRONICS ENGINEERING

ME003-2024

On the Feasibility of a Robotic Seaplane with 3D Printed Wings

Otto Walker

ABSTRACT

With the rise in interest in conservation of the environment, an increasing number of groups are looking at efficient ways to monitor and preserve remote areas of wilderness. This report focuses on the design and validation of an Unmanned Aerial Vehicle to navigate to and monitor remote bodies of water such as lakes, through both a fixed wing and a hull to land and takeoff on the water. The Unmanned Aerial Vehicle is designed to be cost effective and easy to repair, with 3D printed, easily assembled wings. This report considers the specific materials and techniques required to create a pair of wings to carry a boat between areas of water, delving into concepts of weight-saving 3D printing, determining wing shape and size from mission-specific requirements, and methods of attachment to preexisting unmanned surface vehicles. This report also considers the electronic requirements of such a multi-modal vehicle, including the necessary framework to design an autonomous system for flight and water sample gathering. Finally, this report details the tests conducted on the prototype created, discussing where the design worked, benefits and downsides of the specific design choices made throughout the project, and where future researchers could build on the current research to further the field. This includes full automation, a working surface vehicle platform, and integrated sensors to continue the vision of more effective ecological prevention action. The use of this project is in the speed with which cheap, strong wings can be created for prototyping hybrid fixed wing drones, with enough quality to be incorporated in a fully realised design, as well as the furtherment of the field of multi-modal unmanned vehicles, which is currently lacking.

DECLARATION

Student

I, Otto Walker, hereby declare that:

1. This report is the result of the final year project work carried out by my project partner (see cover page) and I under the guidance of our supervisor (see cover page) in the 2024 academic year at the Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, University of Auckland.
2. This report is not the outcome of work done previously.
3. This report is not the outcome of work done in collaboration, except that with a project sponsor as stated in the text.
4. This report is not the same as any report, thesis, conference article or journal paper, or any other publication or unpublished work in any format.

In the case of a continuing project: State clearly what has been developed during the project and what was available from previous year(s):

Signature: ______________________

Date: 13/10/24

Supervisor

I confirm that the project work undertaken by this student in the 2024 academic year ~~is~~ / **is not** (*strikethrough as appropriate*) part of a continuing project, components of which have been completed previously.

Comments, if any:

Signature: ______________________

Date: 13/10/2024

Table of Contents

Acknowledgements . . . . **vii**

Glossary of Terms . . . . **viii**

Abbreviations . . . . **viii**

1 Introduction **1**
1.1 Background & Motivation 1
1.2 Scope 2
1.3 Objectives 2
1.4 Summary of Technical Work 2

2 Related Work **3**
2.1 Unmanned Surface Vehicles 3
2.1.1 Waterjet-Powered Robotic Speedboat 3
2.1.2 Autonomous Sailboat 3
2.1.3 Autonomous Underwater Vehicle 4
2.1.4 Machine Learning Based Unmanned Surface Vehicle 4
2.1.5 Modular Unmanned Surface Vehicle 4
2.1.6 Unmanned Marine Vehicle 4
2.1.7 Comparison and Discussion 5
2.2 Unmanned Aerial Vehicles 5
2.2.1 Bioinspired Retractable Wings 5
2.2.2 Animal Tracking Autonomous Octocopter 6
2.2.3 Computer Vision-Enhanced Quadcopter 6
2.2.4 Landmark-Identifying Fixed Wing UAV 6
2.2.5 Search and Rescue UAV 6
2.2.6 Photo Logging UAV 6
2.2.7 Comparison and Discussion 6
2.3 Autonomous Sea-Air Multi-Modal Vehicles 7
2.3.1 Wing/Sail UAV/USV 7
2.3.2 Flapping Wing Microrobot 7
2.3.3 Comparison and Discussion 7
2.4 Discussion 8

3 Design **8**
3.1 Wing Design 9
3.1.1 Lift Equations 9
3.1.2 Airfoil Choice 9
3.1.3 Wing Design Choices 10
3.1.4 Aileron Design 10
3.2 3D Printing 11
3.2.1 3D Printing Methods 11
3.2.2 Designing for 3D Printing 11
3.2.3 Price of Material for 3D printing 12
3.2.4 Material qualities of LW PLA 13
3.3 Electronics and Autonomous Capabilities 15
3.3.1 Autonomous Groundwork 15
3.3.2 Electronics 15

3.3.3 Electrical Component Justification 15

4 Experimental Data 15
4.1 test Flights 15
4.1.1 Air Capabilities 18
4.1.2 Water Capabilities 20
4.1.3 Battery Life Estimates 20

5 Discussion & Conclusions 21

6 Suggestions for Future Work 21

References 21

List of Figures

Figure 1 (a), (b) Front and rear view of New Dexterity's speedboat prototypes, showcasing 3D printed waterjet nozzle [1]. (c) University of Texas' USV with solar panel and bathymetric sensors [2]. 4
Figure 2 (a) Extended and retracted view of New Dexterity's retractable wings [3]. (b) NTNU's drone platform used for its airdropping case study [4]. . 5
Figure 3 (a) Imperial College London's SailMAV with wings upturned to act as sails [5]. (b) Harvard University's microbot, with electrolysis chamber in yellow [6]. 7
Figure 4 Annotated, exploded view of the finalised prototype. 8
Figure 5 (a) Graph of Cl vs. Cd. (b) Graph of Cl vs. Angle of Attack. Both for the NACA 4412 airfoil at Re=200,000 (Airfoil Tools). 10
Figure 6 Sketch of wing section, split into aileron and main wing 11
Figure 7 (a) Visualisation of shape that was boolean subtracted from solid airfoil piece to create wing internals. (b) One layer of wing architecture after slicing, showing path taken and supports for holes. 13
Figure 8 (a) Damage to the tail after a crash landing. (b) Replacement tail part, printed on a Prusa Mini using LW PLA. 14
Figure 9 Block Diagram of vehicle electrical system. 16
Figure 10 Completed project prototype before testing. 16
Figure 11 (a) Graph of Altitude in meters vs. time in seconds. (b) Graph of Roll angle in degrees vs. time in seconds. (c) Graph of velocity in meters per second. All from test flight 3, taken from Pixhawk flight logs. 18
Figure 12 Demonstration of the vehicle's ability to turn in air using ailerons. Image from test flight 3. 19
Figure 13 The vehicle at the apex of it's vertical climb, having stalled but not yet started falling. Image from test flight 1. 19
Figure 14 The vehicle showcasing a smooth liftoff from the ground, thanks to automatic stabilisation from the Pixhawk controller. Image from test flight 4. 19
Figure 15 Battery life graph obtained from Pixhawk during test flight four. . . . 20

List of Tables

Table 1 Estimated Component Masses 9
Table 2 Electronic Equipment Parts List 17

Acknowledgements

I would like to acknowledge first my project partner, Isara Nua, without whom this undertaking would be impossible, for his dedication to the project, bringing skills in 3D design and aerospace calculations, and for his development of skills in drone programming for the project.

I would like to also acknowledge Dr. Minas Liarokapis, my supervisor, for guiding the project's direction and for always making time in his demanding schedule to help with ideas and executions, including video call meetings from opposite timezones.

Lastly, I would like to acknowledge Angus Lynch, as without his guidance and vast knowledge of drone systems and electronics, the project would likely have started an electrical fire.

These people have been invaluable to the writing of this paper, and I wish them all the best going forward.

Glossary of Terms

Term	Definition
Chord	The distance between the leading and trailing edges of an airfoil
Span	The distance from one wingtip to the other
Aileron	A hinged surface in the trailing edge of an aircraft wing, used to control roll around the longitudinal axis.
Vase Mode	A 3D printer setting in which every layer is printed in one line with no overlap or pauses.
multi-modal	Having several modes. In context of drones, having the ability to locomote in multiple environments.

Abbreviations

NACA	National Advisory Committee for Aeronautics
PLA	Polylactic Acid
LW	Lightweight, used in conjunction with PLA to refer to a specific material
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UMV	Unmanned Marine Vehicle

1. Introduction

1.1 Background & Motivation

Since the introduction of drones to the consumer market and the increase in popularity of Remote Control vehicles, the affordability of flight-enabled autonomous vehicles has only increased. However, while small, cheap drones for children are easy to manufacture and easier to break, drones used in industry are fewer, due mainly to higher operating costs and higher safety standards. It is estimated that for drones to be financially viable in a competitive industry field such as healthcare logistics, servicing hospital stock requirements and transporting patient samples to test centres, costs may need to be reduced to less than 20% of the current requirements [7]. While drone manufacture costs are decreasing, automation algorithms are becoming more efficient and independent leading to lower maintenance and operation costs, and commercial drone market sizes across the world are increasing at projected compound annual growth rates of over 10%, it is still believed that a costs reduction of that magnitude is unfeasible. Drones used in conservation also face issues with pricing, such as the requirement for longer missions to reach more remote areas bringing up the issue of nonstandardised component durability ratings wherein it is unclear when to service or replace parts on the drone [8] leading to either higher safety factors and more expensive equipment or dangerous work practices, as well as the exponential cost of more efficient batteries to allow travel on longer missions to justify drone use rather than human. Too, 3D printing is becoming more commonplace, with effective printing units available for consumers and immeasurable applications for both industry and personal use forcing fast improvement of the field [9]. 3D printed items are also cheaper to produce, and faster to acquire, than commercial alternatives [10], leading many different fields to adopt 3D printing practices. Recently, more and more different types of filaments are being used, also. This further increases the versatility of the 3D printer, where in addition to the currently popular plastics such as polylactic acid, filaments can contain mixtures of different materials affecting characteristics such as strength, melting temperature, reactions to weathering, and even change characteristics such as print volume. With pollution levels in bodies of water increasing in New Zealand and worldwide [11], it is becoming clear that water must be monitored and protected to preserve the reliant plant and animal life. The main obstacle to this is the manpower, and associated cost, required to periodically check every remote waterway in the world, leading often to waterways going unchecked and therefore unmaintained. Autonomous boats and planes are useful in this, however a boat cannot travel overland to isolated locations, and a plane cannot take water samples and do close analysis of water while flying. Rotary wing drones, while capable of taking water samples, lack long range ability and are more expensive to manufacture at larger scales to carry more sensing equipment, so attempts to monitor waterways remotely have been less successful than desired [12]. While autonomous sea-air vehicles have been detailed in literature [5, 6], they either respectively rely too heavily on the environment for efficient locomotion, or employ methods of locomotion that are unsustainable at a size reasonable to mount and transport sensing equipment. This field is surprisingly short on research, as multi-modal drones have a large range of applications, especially those combining flight and water traversal abilities. In addition to the aforementioned waterway monitoring, which is an excellent example due to the combination of New Zealand's tourism-attracting natural environment and their problem with pollution, multi-modal vehicles have wider applications such as cargo transport to forested or mountainous areas where a regular fixed wing UAV may not be able to land safely due to lack of flat ground whereas the multi-modal vehicle is able to use the waters surface as an efficient runway for landing. To this end, this paper details a set of 3D printed wings for mounting on a surface vehicle to facilitate multi-modal travel, with emphasis on affordability and autonomy. The drone has been designed with the task of travelling to and analysing multiple inland bodies of water for conservation in mind, and while the research in this paper could help any potential consumer, the drone is intended to be used by a company such as a contractor to a Government branch. The affordability aspect is necessary due to the requirement that for conservation work to be funded, the project must be seen to appeal to Government budgets, or be in the realm of affordability for private sponsors. In regards to autonomy, the elimination of a human operator cuts down on manpower and training requirements, and allows the drone to continue operating when no human supervisors are present.

1.2 Scope

This project's scope is to develop a method of 3D printing wings, tails, and flight control surfaces for use in sea-air multi-modal robot applications, so as to extend the autonomous range of unmanned vehicles beyond that of waterways, and towards full autonomy. The wings should be low cost and easily repairable, so as to be available to conservationist groups without requiring a large budget. This includes designing also a method of attaching the components to the boat platform without interfering negatively with performance as a boat, as well as a motor mount, and including electronic capabilities for full automation and to allow testing of the wings.

1.3 Objectives

The objective of this project is to design and develop a modular flight kit that can be attached to a surface vehicle platform to allow multi-modal travel. Specifically, the research objectives of this project are:

- To design and construct a prototype multi-modal vehicle by designing a flight kit and adapting it to an already existing surface vehicle.
- To describe the flight kit design and underlying techniques in enough detail that future researchers are able to not only manufacture the kit but modify it to suit their specific needs.
- To validate experimentally the flight kit's functionality.
- To validate the statement that the flight kit is economic and easy to manufacture and repair.
- To prove that theoretical automation of the developed prototype vehicle is possible.
- To analyse the performance of the prototype in real-world scenarios.

1.4 Summary of Technical Work

In this project we designed, printed, and assembled modular wings out of LW PLA, reinforced with carbon tubing, and tensioned in place by high-tensile fishing line. We printed ailerons out of LW PLA then attached them to the wings using carbon fibre rods as axles. We designed and printed a table-shaped platform out of generic PLA for creating a high mount of the wings on a provided remote controllable boat, fastened in place using nuts and bolts. We designed, printed, and assembled a modular plane tail consisting of a horizontal and two vertical stabilisers out of LW PLA, reinforced with carbon tubing, and tensioned in place with zip ties. We designed and printed a plane tail elevator out of LW PLA then attached it to the tail using carbon fibre rods as axles. We designed and assembled structures from 3D printed PLA and carbon tubing to mount the tail, two motors and two propellers to the front of the boat. We installed a servo in each wing to actuate the ailerons, and a servo in the tail to control the elevator. We soldered extensions to the servo and motor units, and connected them to a Power Distribution Board to allow control from a Pixhawk flight controller. We secured a battery to the vehicle and connected it to power the electronic system. We validated our design with extensive real-world testing, documented the resilience of reinforced, 3D printed structures and proved it's ability to be easily repaired and have parts replaced. We also demonstrated that the vehicle possessed the functionality to be used as a platform to build a system capable of autonomous flight using the prototype with the power of the Pixhawk flight controller.

2. Related Work

This literature review provides an overview of relevant literature to the project of creating a hybrid sea air vehicle with autonomous capability. The literature review focuses on similar projects of unmanned vehicles, to determine which techniques employed in previous work were useful and which are to be avoided. The review is segmented into three separate sections, each exploring a separate type of unmanned vehicle. The categories of unmanned vehicles are those that are pertinent to the project, being those of autonomous surface vehicles, due to the semi-aqueous nature of a seaplane, those of autonomous aerial vehicles, due to the requirement of flight and the largely unguided way in which it must be achieved, and finally autonomous sea-air multi-modal vehicles, to ensure the research has not already been explored, and to draw from the inspiration of other literature in the chosen field. Each section will explore the most impactful findings from the described field, with emphasis on those closely related to the undertaken project. Finally, there will be a discussion on the current research, and it's relevance to the project.

2.1 Unmanned Surface Vehicles

In this section, a variety of different types of autonomous water-based vehicles will be presented, and comparisons made. Attention will be paid to the method of creating autonomy, any sensor capability in the design, and the physical design propulsion methods. Usage in conservation-related fields will also be commented on where relevant.

2.1.1 Waterjet-Powered Robotic Speedboat

To create a platform for further research, the New Dexterity Research group at the University of Auckland [1] present a catamaran, waterjet-propelled autonomous speedboat. The boat is designed to be cost effective and easy to maintain, and as such all structural parts, both hull and waterjet system, can be 3D printed. The design of the hull allows for navigation in shallow water and a minimal intrusion on sealife.

2.1.2 Autonomous Sailboat

Developing a craft for the Microtransat competition, researchers at the Faculty of Engineering of the University of Porto [13] present an autonomous sailing boat with a design emphasis on low-power, long-range missions. The researchers posit that due to the renewable, free nature of wind energy, their ship is superior to power driven ships. It employs a simplified version of Linux coupled with custom peripherals to allow full autonomy on the

Figure 1 (a), (b) Front and rear view of New Dexterity's speedboat prototypes, showcasing 3D printed waterjet nozzle [1]. (c) University of Texas' USV with solar panel and bathymetric sensors [2].

water, and can utilise a few kilograms of cargo space to transport mission-specific sensors and shipments.

2.1.3 Autonomous Underwater Vehicle

Also from the Faculty of Engineering of the University of Porto [14], researchers present an autonomous underwater vehicle for various underwater mapping and monitoring applications. The vehicle is able to move directly in the vertical plane, and at speeds of up to two meters per second horizontally. It is designed for flexibility in missions, with space for a payload to help with tasks such as pollution monitoring, sonar mapping, or mine countermeasures. The vehicle is also designed heavy, at thirty two kilograms, due to the low priority of speed or fuel use, preferring instead more sensors and the required depth protection architecture.

2.1.4 Machine Learning Based Unmanned Surface Vehicle

Researchers at the University of Texas [2] present an Unmanned Surface Vehicle (USV) for bathymetric surveying of dangerous or shallow areas and as a low-cost platform for developing the area of machine learning based reconnaissance systems. The vehicle is designed for inland bodies of water, is solar powered, and has the processing capability to use the data it is collecting to make decisions about its actions.

2.1.5 Modular Unmanned Surface Vehicle

Researchers at Purdue University [15] present a small USV platform designed with the capability of water quality monitoring. The USV is designed for modification and specialisation with an open source, 3D printed modular design. It interfaces via Bluetooth with an android application that displays the sensor and GPS output, and allows for manual control.

2.1.6 Unmanned Marine Vehicle

Researchers from the Marine Robot Center at the Korea Institute of Industrial Technology [16] present an Unmanned Marine Vehicle (UMV) consisting of a USV working in tandem with an Unmanned Underwater Vehicle (UUV) by way of connection via underwater cable. The purpose of this project is to provide a platform for ocean exploration and fill gaps in current research on tandem unmanned surface and underwater vehicles. The two vehicles are used for real-time aquisition of marine data.

2.1.7 Comparison and Discussion

In the reviewed texts, a variety of different combinations of hull design and propulsion mechanism are explored, each with different benefits. The texts also designed for differing use cases, but many featured a modular, 3D printed design, which seems to be becoming the standard for low-cost marine research platforms as 3D printing becomes more accessible. Two of the papers detailed underwater vehicles, which while not fitting directly under the umbrella of unmanned surface vehicles, still provide valuable insight into possibilities regarding a more thorough surveying of aquatic environments, such as how water quality may differ with depth. Of note is the volume of papers that stress the environmental aspect of their designs, such as wind and solar power, and the choice of sensors for detecting pollution and similar. These papers all had fully realised vehicles, however many of them were in anticipation of future work, so less consideration was put into specific goals, and more into compiling information for later use and keeping the vehicles highly modifiable by sacrificing possible enhancements for specific tasks. Surface vehicles also have little inclination to restrict weight, often preferring instead to add weight where necessary, such as ballast, to obtain the best performance on the water. This means there was little in the way of research useful to the airplane aspect of the project, however the research will be invaluable for any future work done on the project.

2.2 Unmanned Aerial Vehicles

In this section, papers relating to fixed wing Unmanned Aerial Vehicles (UAVs) and UAVs with a focus on conservation are compiled, and comparisons made. While this segment contains examples of rotary wing UAVs, little design inspiration can be gleaned due to the hugely differing nature of their method of locomotion compared to fixed wing UAVs, therefore the summaries will focus on features related to the design of fixed wing UAVs, and features from both types of drone that are conservation-specific or intended for low-cost fabrication.

2.2.1 Bioinspired Retractable Wings

Researchers at the New Dexterity Research group at the University of Auckland [3] present a pair of transforming, tendon-driven wings covered by feathers made of PET film and carbon fibre in the shape of the NACA 4412 aerofoil and weighing 3kg. The wings allow for a 48.6% reduction in area, due to the overlapping of the "feathers". The wing has a lower lift coefficient compared to a fixed wing, but keeps a linear lift coefficient change when changing angle of attack. As well as testing concepts from nature, the project aims

Figure 2 (a) Extended and retracted view of New Dexterity's retractable wings [3]. (b) NTNU's drone platform used for its airdropping case study [4].

to create a vehicle greater than VTOL, with the folded wings exhibiting remarkably less drag and allowing more efficient and stable hovering of drone platforms.

2.2.2 Animal Tracking Autonomous Octocopter

Researchers at the University of Sydney [17] present an autonomous 8 rotor drone for the tracking of small, fast animals via tagging with small radio transmitters. After onboard processing of the signal occurs, the drone can provide the location of the animal within a 50m area. Experimental tests showed this method to be as fast or faster than trained human operators employing the same strategy from the ground. This vehicle was designed for wildlife conservation, allowing endangered wildlife species to be easily tracked with far less use of human operators than conventional methods.

2.2.3 Computer Vision-Enhanced Quadcopter

Researchers at ETH Zurich [18] present an autonomous quadrotor drone flying using computer vision. A fusion of IMU and vision information is presented to increase accuracy of camera pose estimation, and a basic setup is shown for marker-based autonomous flight. The focus of this paper is the software development for the vision-based autonomy, made possible by the Pixhawk system, and the project is the basis for the Pixhawk branded drone standards and products, used in many drones today.

2.2.4 Landmark-Identifying Fixed Wing UAV

Researchers at the Norwegian University of Science and Technology [4] present a fixed wing UAV for autonomous airdrops of packages. The UAV uses onboard machine vision to identify landmarks and find its target drop area, then releases the object to land on the target. This is to step towards full autonomy, as unlike previous airdropping UAVs, the vehicle does not have to know the precise location and can instead rely on visual clues for guidance. The project does appear to have strong military applications.

2.2.5 Search and Rescue UAV

Researchers in the Centre for Automation and Robotics at the Universidad PolitÂŽecnicade Madrid [19] present an aerial robot for search and rescue inside an unstructured building. The drone uses a multiple learning-based technologies to perform high-level missions autonomously, including using a convolutional neural network model to classify targets, and image based visual servoing to interact with the target.

2.2.6 Photo Logging UAV

Touted as a low cost autonomous vehicle for conservation, researchers from ETH Zurich and the University of Zurich [20] present an aerial vehicle to photograph a set area and creat a mosaic picture of the entire area. This allows for the observation of large animal habits, human intrusion such as logging, and statistics such as plant biodiversity.

2.2.7 Comparison and Discussion

In the reviewed texts, multiple UAVs are detailed. Multiple papers detailed ways to introduce machine learning to autonomous drone flight, to high levels of success. However, most drones being researched for this purpose are multirotor drones, due to having a wider range of applications suited to high level machine learning thanks to the ability to hover and move in all axes uninhibited. Topically, the UAV for package airdrops could be used

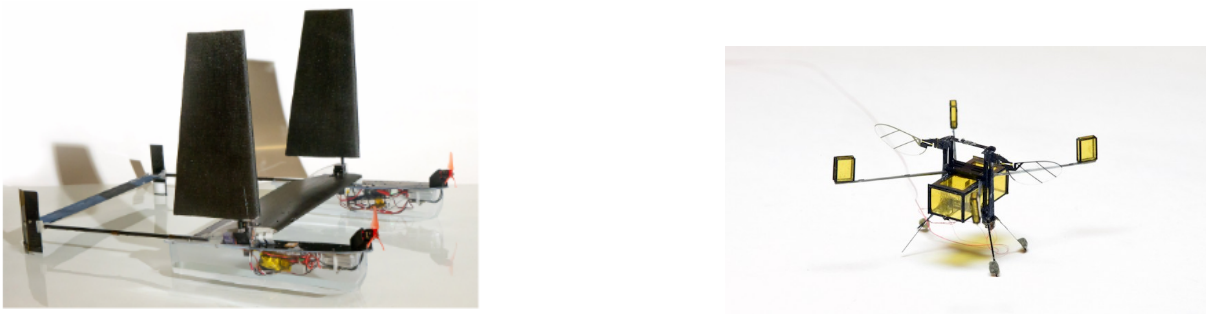

Figure 3 (a) Imperial College London's SailMAV with wings upturned to act as sails [5]. (b) Harvard University's microbot, with electrolysis chamber in yellow [6].

to drop other autonomous vehicles to remote areas, such as small, self-sustaining water based craft for continuous monitoring of inland bodies of water, and the drone for creating photograph collages of the terrain could be used for remote monitoring of visual signs in inaccessible areas.

2.3 Autonomous Sea-Air Multi-Modal Vehicles

In this section, drones with both air and water capabilities are detailed. This area of research is most pertinent to the project at hand, however available research is lacking in volume. While landing and taking off from the waters surface is similar to that of land, key differences such as water friction, tension, and waves, as well as the changes in boat behaviour at high speeds required for takeoff such as porpoising necessitate the control architecture of takeoff and landing to differ to that of UAVs that launch from land for automation purposes.

2.3.1 Wing/Sail UAV/USV

Researchers in the Imperial College London [5] present an autonomous sailboat/fixed wing drone for applications such as water sampling. The drone employs a wing that can fold in three parts, allowing it to also function as a sail. It is capable of takeoff from the water surface, allowing moving from one body of water to another for purposes such as water sampling. The vehicle has a wingspan of 0.96m, and a cruising speed of 10.8m/s. The drone is designed to move between bodies of water on fast missions.

2.3.2 Flapping Wing Microrobot

Researchers at Harvard University [6] present a microrobot to locomote in both air and water. The robot uses a flapping wing design for both flying and swimming, and electrolysis of water to create a gas explosion for takeoff from the waters surface. The vehicle utilises phenomena only available at the micro scale, and also overcomes problems of micro scale such as surface tension.

2.3.3 Comparison and Discussion

Although research in this specific sub-field is sparse, the two papers detailed show its breadth. The wing/sailboat is an inspired design, and would work well in open water areas where wind is not blocked, but may have issues carrying larger payloads. It is also not designed to be low cost, but rather to further research, so cost and difficulty of repair are higher. The folding wing design, while novel, may not be the most effective in remote areas where assistance in case of failure is difficult, and hazards may be more abundant. The microbot is less effective for large scale operations, but shows the wide range of designs multi-modal robots can have and introduces the concept of using the same actuators for moving in both mediums, as well as the interesting possibilities that come with micro design. The designs are very well planned and executed, and while both are fully functional, the designs may be too complex and hard to manufacture for industrial and real world applications.

2.4 Discussion

In conclusion, this literature review explored research on the types of drones most pertinent to the project, including those of unmanned surface vehicles, unmanned aerial vehicles, and finally the small field of unmanned multi-modal vehicles capable of locomotion in both water and air. The findings were thus: high numbers of groups were found to be adopting the concept of 3D printing a boat hull for ease of prototyping, manufacture, and repair. Few groups were innovating on fixed wing UAV design outside of New Dexterity's bioinspired retractable wings, prefering instead to focus on the software element of autonomous drone design, with multiple integrating machine learning to the flight controller to create a more effective, 'smarter' drone. Conservation efforts in both fields were high, with USV researchers focusing largely on ocean exploration and water monitoring, as well as passive forms of environmental friendlyness such as wind and solar power. Researchers of UAVs, having a wider range of possible activities, created drones with more diverse conservation efforts, such as animal tracking and photo logging of the environment, both of which are large sub fields in the field of conservation work.

3. Design

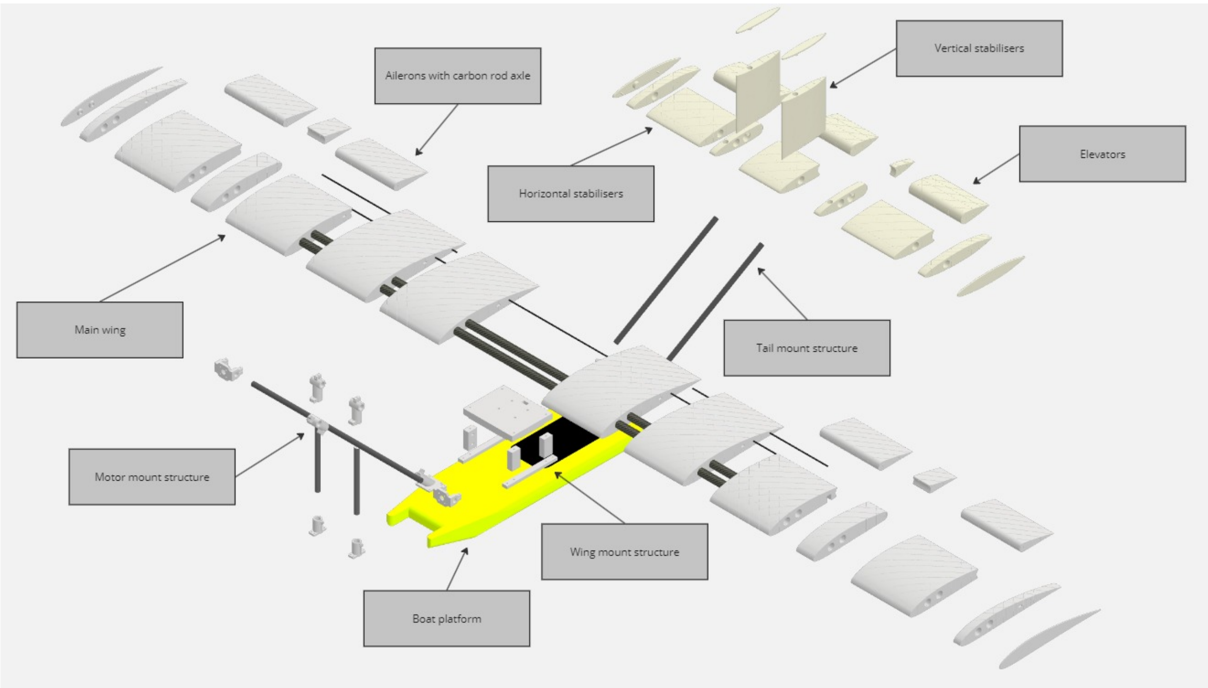

Figure 4 Annotated, exploded view of the finalised prototype.

3.1 Wing Design

In this section, every design choice and technique for developing the wing and tail of the vehicle is detailed, including calculated variables for theoretical validation, design choices such as airfoil choice, and the entire 3D printing process required for fabrication. Also encompassed is discussion on the benefits and downsides of each choice, and a cost breakdown of the specific materials required for fabrication.

3.1.1 Lift Equations

To design a flight kit for a boat, first the theoretical calculations of how much lift to generate to achieve flight are required. To this end, the lift equation was employed to give estimates for wing size at the expected weight and with the available thrust. The lift equation is as follows:

$$L = Cl * \frac{\rho V^2}{2} * A \tag{1}$$

Where L is lift in Newtons, Cl is the Lift coefficient, ρ is the density of the medium in kilograms per meter cubed, V is the velocity of the craft in meters per second, and A is the wing area, in meters squared. The Lift coefficient is obtained from the Airfoil, detailed below.

Determining velocity required for takeoff, known as stall speed, is simply determining the force needed to counter the weight of the craft, with $F = ma$. The masses of the boat and required electronics were measured, and the required support structure for the wings and electronics was estimated.

Table 1 Estimated Component Masses

Piece	Mass (kilograms)
Boat	1.173
2x propeller motor	0.164
Support Structure	0.2
Total	1.537

The stall speed was then arbitrarily chosen based on common sense values and the lift coefficient then wing area were calculated using Eq 1 and 2, then iterations performed until stall speed and wing area were both reasonable values. A chord length of 300 millimeters was chosen, due to 3D printing restrictions detailed below. From this the wingspan of 1.5 meters can be calculated. The stall speed with this wing area is then ~35 kilometers per hour.

3.1.2 Airfoil Choice

The airfoil is important, as it determines lift coefficient, and therefore allowable weight for the whole aircraft. As the wings were designed to transport a sensor-heavy boat to remote areas, a high lift coefficient airfoil was required. Since the relationship between lift coefficient and drag coefficient of an airfoil is determined by Reynolds number, it was required to calculate it to choose the most advantageous airfoil. The Reynolds number calculation for flow around airfoils is:

$$R = \frac{Vc}{v} \tag{2}$$

Where R is the chord Reynolds number, V is flight speed in meters per second, c is chord length in meters, and v is the kinematic viscosity of, in this case, air at room temperature, in meters squared per second. From these parameters, the Reynolds number can be calculated as 200,000 and airfoil lift vs. drag graphs can be compared to find an optimal airfoil design. The airfoil chosen was NACA 4412. This numbering is a shorthand for descriptions of its characteristics, in this case being 4% maximum camber as a percentage of the chord, 4 tenths of chord length maximum camber position from the airfoil leading edge, and 12% thickness of the airfoil as a percentage of the chord.

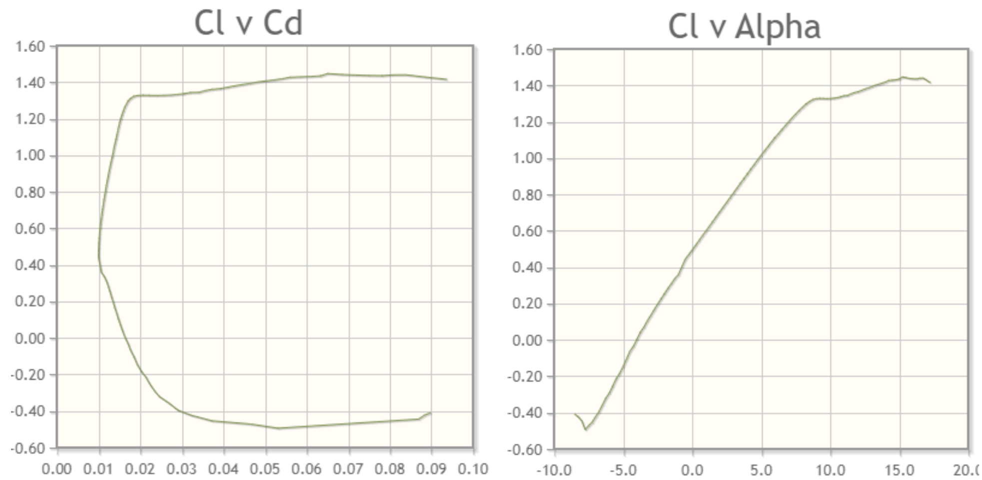

Figure 5 (a) Graph of Cl vs. Cd. (b) Graph of Cl vs. Angle of Attack. Both for the NACA 4412 airfoil at Re=200,000 (Airfoil Tools).

3.1.3 Wing Design Choices

once requisite wing design parameters are determined theoretically, physical creation of the wing can begin. The wing was decided to be 3D printed for reasons of cost and repairability in keeping with the scope of the project, and as flight is a requirement, was designed to be as light as possible. The wing also had to have a way of keeping the separate modular 3D printed parts rigid and in shape, a way of attachment to the boat, and a way to influence direction. To keep the modular 3D printed parts together and rigid, two carbon fibre tubes were used as wing spars, simultaneously arresting rotation and providing essential rigidity to the shape. A string was then threaded through the tubes and tied to the ends of the wings, stopping any possible sliding of the printed parts on the tubes. To attach to the boat, a table was designed and printed, and the wings fastened to it by way of bolts through the carbon fibre tubes. Once the table was bolted to the boat, the entire assembly was secure and capable of withstanding the loads applied from generating lift.

3.1.4 Aileron Design

To influence direction, ailerons were installed, also made of 3D printed material and using carbon fibre rods as axles for rotation. They are attached by way of rods to servo motors mounted in the main part of the wing, allowing for $\sim$35 degrees of rotation above and below the chord line. This rotation was measured in stable conditions while not in flight, and lowers by $\sim$15% when exposed to high winds and lift and drag forces. The ailerons are 30% of the wing chord and 53% of the wingspan, both measurements within margins recommended by Professor Dieter Scholz in [21].

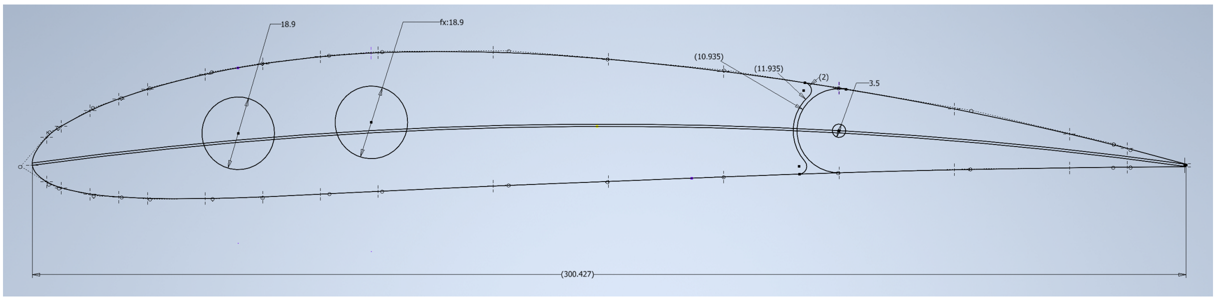

Figure 6 Sketch of wing section, split into aileron and main wing

3.2 3D Printing

In this section, all considerations of 3D printing are explained, including the material used, the modelling techniques and printer slicer settings required to fully utilise the material, the benefits and downsides of printing with the material, a cost breakdown of the material, and the repairability and maintenance of the piece after printing.

3.2.1 3D Printing Methods

All wing surfaces in the project were 3D printed, and to save as much weight as possible, the wings must be 3D printed as light as possible. In pursuit of this, multiple different techniques and nonstandard practices were employed simultaneously. First, the material used was Esun LW PLA, a lightweight version of PLA, for multiple reasons. One, LW PLA offers a 45% reduction in density compared to regular PLA, from 1.2 grams per centimeter squared for PLA to 0.54 grams per centimeter squared for LW PLA. Two, LW PLA foams at high temperatures, from 210-270°Celcius, increasing volume by up to 120%. Second, the wing pieces were printed in vase mode, a printer setting in which the printer never stops extruding, and each wall is one layer thick. This was in fact made possible by the greater volume, as regular PLA extrusion width is too fragile to support the forces required while the larger width afforded by the foaming capabilities of LW PLA allows for thicker, more resilient walls. Extrusion rate also affected the strength and weight of the print, being the volume extruded over time. Tests were run on the material to determine the most efficient temperature and extrusion rate, increasing temperature or decreasing extrusion rate until a balance between weight saving and strength was achieved. The final values from the rounds of testing were 270°Celcius and 0.75x extrusion rate, using a 0.4 millimeter nozzle and 0.2 millimeter layer height. The printers available for this project were Prusa brand and had a maximum bed size of 250 x 210 x 220 mm, which is relatively standard for consumer-grade 3D printers. For this reason, a 300mm chord length was decided, as that is the maximum chord length the NACA 4412 Airfoil can be and still be maneuverable into a printable position on the plate.

3.2.2 Designing for 3D Printing

As stated above, the wing pieces were printed in vase mode with walls being one layer thick, which is not at the current time attainable with available slicing software and basic 3D part design. The 3D models must be designed specially for these circumstances, including creating the support structure inside the piece which is usually generated by the software, and designing supports for the holes required to house the spars. The 3D models must be manipulated such that when sliced, the single line per layer followed the optimal path for both strength and printing stability, as shown in figure 7 (b). Due to wing structures experiencing forces mainly in the vertical direction, the models have have a gap through the chord line of the piece so that layers are joined through the centre and not exclusively at the upper or lower surface, to avoid weak points and maintain the structural integrity of the piece. To create the inner structure in preparation for slicing for the 3D printer, as seen in a boolean subtraction method is employed. This involves creating a shape that when subtracted from the solid wing airfoil piece, leaves surfaces that when viewed from the direction the printing would occur on, form the shape of the wing at that point, including all ribs and spar holes as seen in figure 7. To realise this end, a rib structure, spar holes and servo cabling holes are formed. The support structure is a grid based pattern that continues throughout the piece except where spar holes are located. This is achieved by creating a grid of squares, in the case of these wings 20mm width, giving each line a width of 0.1 millimeters, then extruding the lines between the planes of the airfoil shape. This is achievable with vase mode in a 3D printing environment due to the printers ability to print at up to a $\sim$45°angle, as the material clings to itself to a point, and as such the grid must be aligned offset to the build plate to allow this phenomenon to occur. The holes for spars and aileron axles require specialised support structure in the vertical direction, as the generic support structure throughout the piece does not provide enough support to withstand vertical forces due to the nature of it's grid being at a 45°angle. This can be achieved by way of, again, 0.1 millimeter lines above and below the spar holes. However, to keep to the restrictions of vase mode, one end of the line must end before the outer surface of the model, and the other end must protrude past it to constitute a break in the surface to allow for printing of inner details. Squares and similar shapes can be designed the same way, however if too many breaks in a small area of the surface of the piece occur, such as the 2 millimeter rounds that constitute the back of the main wing in figure 6, a shape that forces a single line around the edge can be used to avoid printing imperfections. The LW PLA material used eases the difficulty of printing in this manner as it's foaming capability allow for much stronger joining of single layers printed next to one another. The information for this process was gleaned largely from Tom Stanton's instructions on 3D printing wings [22], however extrapolation of the methods was required for cutting certain shapes from the wings, such as rectangles that cut into the outside of the wing, rectangles through the inner of the wing, and the design of the aileron wing parting. This design saves weight in the drastically lower volume of filament used due to both vase mode and manually generated infill, while remaining strong enough to withstand forces enacted on it while generating lift. Downsides include the requirement of post-processing due to horizontal voids being impossible to print with this technique, as well as less structural stability in the upwards print-wise direction.

3.2.3 Price of Material for 3D printing

Due to the stated requirement for low cost when fabricating the vehicle, the material cannot be expensive or hard to acquire. Luckily, the LW PLA that is essential to this project is neither. Due to it's popularity as a material for Remote Control hobbyists and people wanting to make light-weight replica items for costumes, LW PLA is not prohibitively expensive, and is stocked at most major filament retailers. The cost per kilogram is between \$65NZD and \$80NZD, depending on supplier. This is compared to generic PLA, which sells for $\sim$\$30NZD, which is a difference of \$50NZD or an increase of 116.7%. However, due to the foaming nature of LW PLA, where regular PLA has a density of 1.2 grams per centimeter cubed, LW PLA has as low as 0.54 grams per centimeter cubed. This affects the price per volume to where PLA costs 0.036NZD/cm^3 and LW PLA only 0.035NZD/cm^3, for a difference in price now of 1 New Zealand cent, or a decrease of 2.8%. This means that LW PLA is cheaper by density that regular PLA. Obviously, this leaves out a lot of factors, such as that PLA and LW PLA each have a range of uses, with

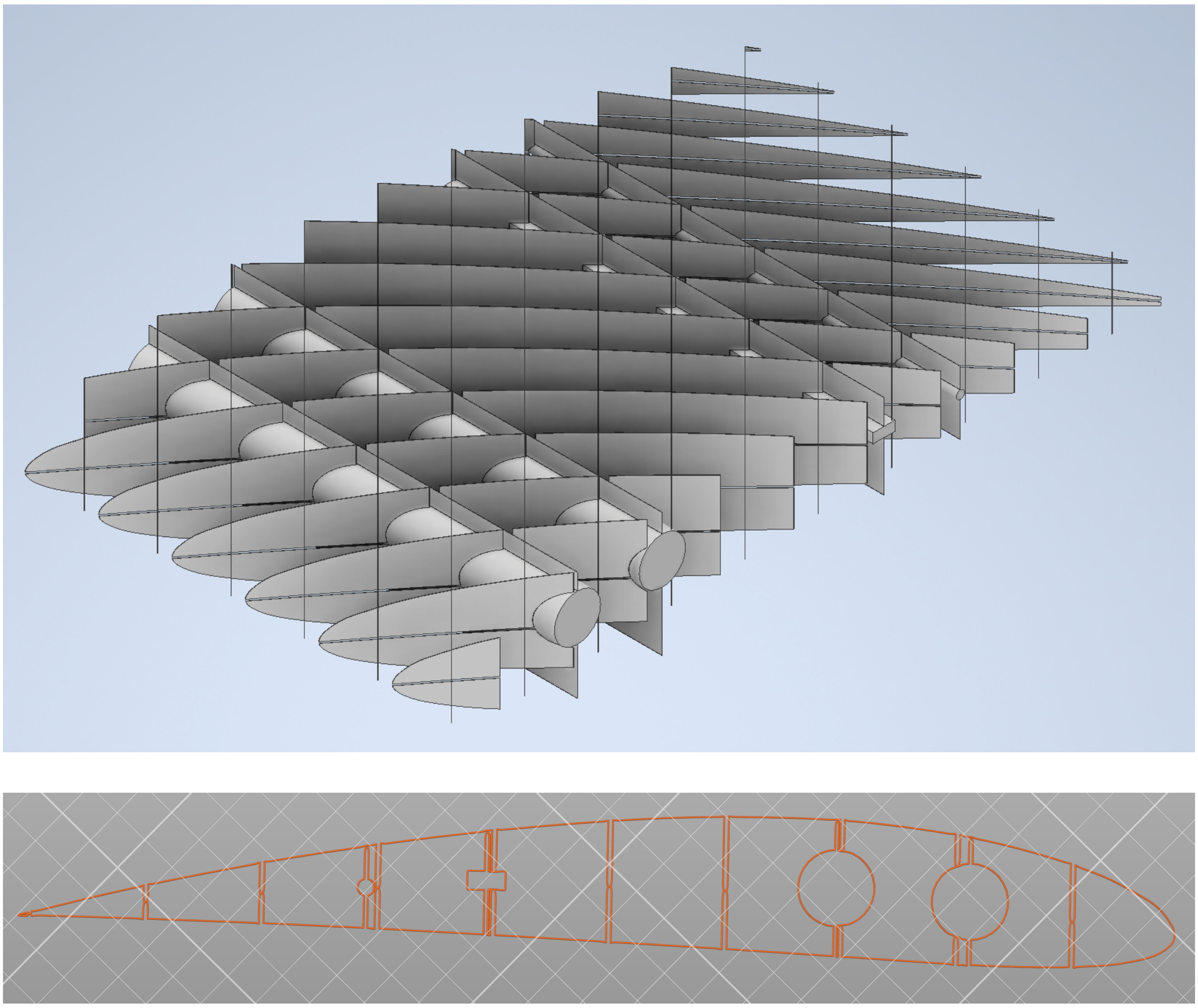

Figure 7 (a) Visualisation of shape that was boolean subtracted from solid airfoil piece to create wing internals. (b) One layer of wing architecture after slicing, showing path taken and supports for holes.

little overlap, that depending on circumstance, LW PLA may not be printed every time at it's highest foaming temperature, and that where PLA is recommended to print with infil and multiple layers, LW PLA is recommended to print in vase mode, as mentioned above. Therefore, while no true comparison can be made between the two, it can be said that LW PLA is similar in price, at least by volume, as PLA, which is regarded as a cheap material considering its myriad uses.

3.2.4 Material qualities of LW PLA

While some reservations may be had about trusting valuable, delicate equipment to the lift generated by a wing consisting of one layer of plastic, they are unfounded. The LW PLA datasheet states the tensile strength as being 32.2 Megapascals (MPa), and it's flexural strength as 41.31MPa. With proper spar support and correctly designed infill, LW PLA has been experimentally confirmed to hold it's shape in the air, and even stay fully intact when dropped from heights of up to 2 meters as shown in figure 13. Even when the LW PLA does break, due to the modular nature of the wing design, as well as the layer lines of the printing creating natural breaking points, the damage is contained to the module that sustained the impact and did not in testing affect any other modules, as seen in figure 8 (a).

Figure 8 (a) Damage to the tail after a crash landing. (b) Replacement tail part, printed on a Prusa Mini using LW PLA.

3.3 Electronics and Autonomous Capabilities

In this section, the electronics required to achieve aerial locomotion are detailed, along with the systems and hardware installed in the vehicle to allow for autonomous flight. Choice of electronic equipment is also justified, and a diagram of the system used is provided.

3.3.1 Autonomous Groundwork

The proposed vehicle will employ autonomous flight capabilities to travel between bodies of water, and while designing hardware-specific autonomous programs was not within the scope of the project, success was found in employing preinstalled programs such as automatic stabilising during test flights, proving the possibility of automation with the current hardware. To configure the Pixhawk controller with the actuators, the UAV-centric Ground Control Station application QGroundControl was used. QGroundControl provides flight control and mission planning for any MAVLink enabled drone, MAVLink being the messaging protocol used by the Pixhawk 4 and multiple other UAV platforms.

3.3.2 Electronics

The hardware system flow is depicted in figure 9, and the specific components purpose is detailed in table 2.

3.3.3 Electrical Component Justification

The Servos were chosen for the project due to their price point and availability. High torque versions of the same servos are available, however the cost is higher and during testing, the ailerons were found to deflect to a satisfactory angle under load and no adverse steering effects were detected. The T-motors were chosen because they had a large safety factor for thrust required to move the vehicle. The Pixhawk 4 was chosen because of it's ease of use and low setup requirement, meaning parts could easily be swapped out of the prototype as it was being tested and controls be remapped. The other pieces of electronic equipment were either recommended peripherals for already chosen equipment, such as the ESCs for the motors, and the transmitter and receiver for the Pixhawk, or they were chosen due to factors such as suppliers being trusted due to there being no noticeable difference between the different brands on the market, such as the BEC and power distribution board.

4. Experimental Data

In this section, the results of the test flights undertaken by the vehicle, as well as estimations of capability in different environments, will be discussed. The estimations are necessary due to certain requirements of a fully functional seaplane being out of scope of this project, such as manufacturing a fully functional, waterproof boat for use with the wing kit.

4.1 test Flights

The vehicle embarked on 4 test flights, 3 of which were successful in that the vehicle achieved liftoff under it's own power. The flights were performed in an open, wind-sheltered area, and the vehicle was placed on grass and allowed to slide on the boat base until liftoff was achieved. All test flights were performed under the same external conditions. The first flight suffered due to a lack of experience with the vehicle, as well as unintended declination of the use of automatic stabilisation provided by the Pixhawk controller in favour of fully manual control. However, despite setbacks, the vehicle reached a measured altitude of 4

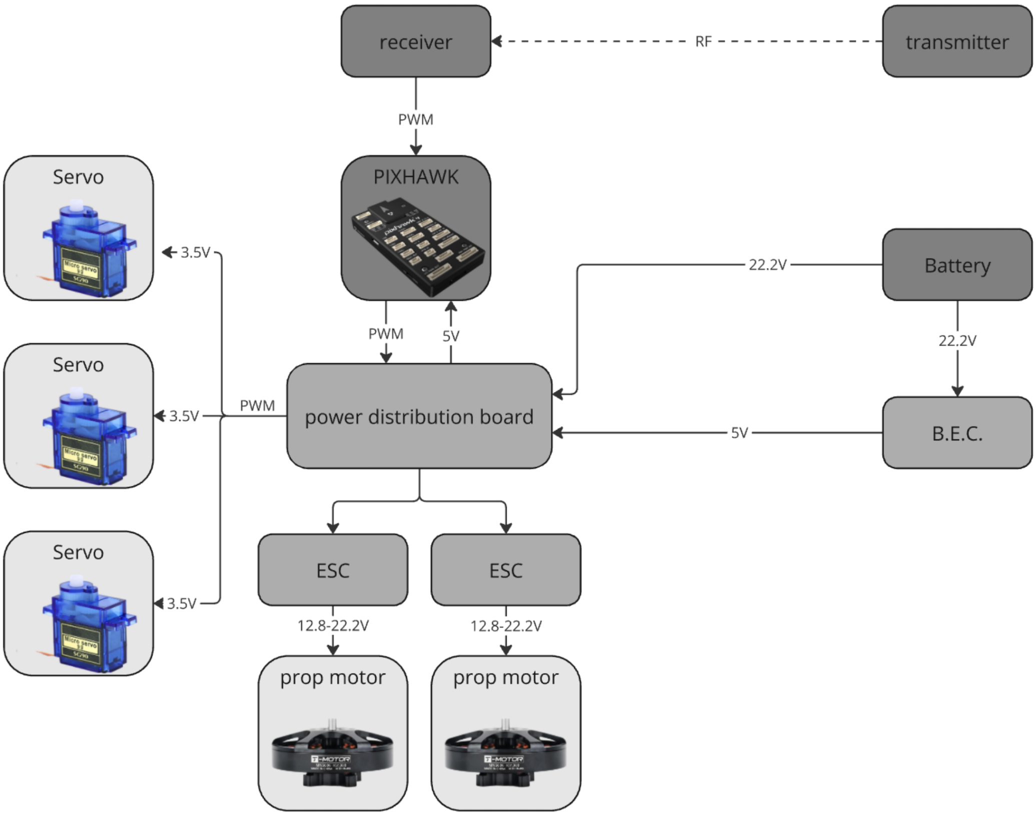

Figure 9 Block Diagram of vehicle electrical system.

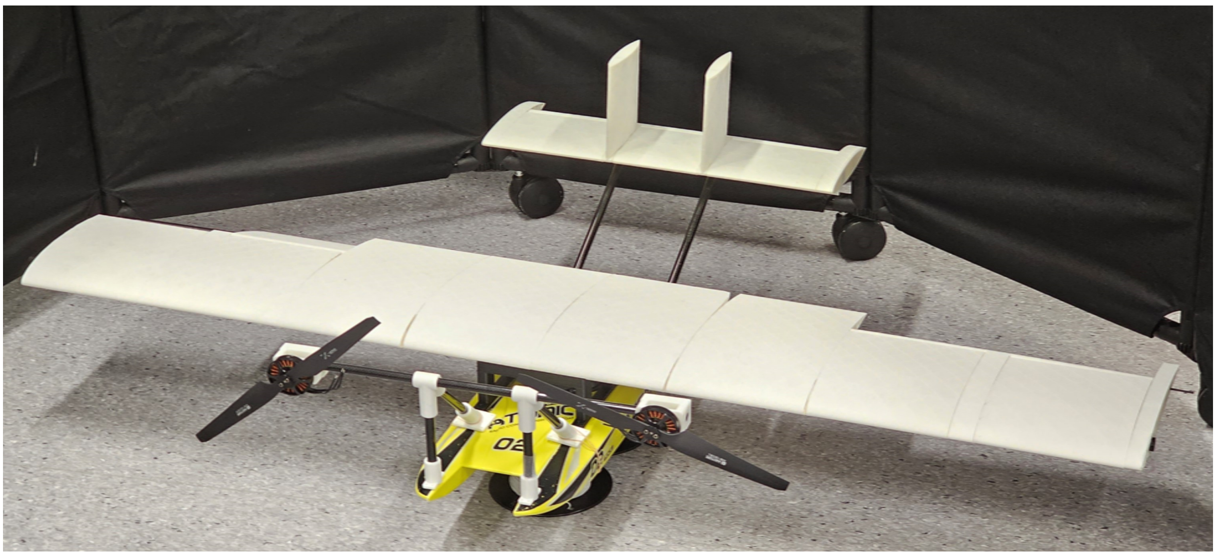

Figure 10 Completed project prototype before testing.

Table 2 Electronic Equipment Parts List

Equipment Name	Description and Use
9g Servo	The actuator for all primary flight control surfaces on the vehicle. This includes both ailerons and the elevator. Controlled via Pulse Width Modulation (PWM) from the Pixhawk through the Power Distribution Board.
T-motor MN5006	The main motor for producing thrust for the vehicle. Capable of completing 450 revolutions per minute per volt. The vehicle contains two of these, mounted in parallel. Controlled via voltage regulation.
Electronic Speed Controller (ESC)	This controls the speed at which the motor spins by reading voltage feedback from the motor, and adjusting accordingly to always spin at the set speed.
Battery Eliminator Circuit (BEC)	Changes the voltage of the battery in order to power lower-voltage components.
Power Distribution Board	Handles splitting power between the different components in the system. Works in tandem with the ESC and BEC.
Pixhawk 4	Autopilot module running the software PX4. Controls all actuators. Interfaces with the transmitter through the receiver. Capable of autonomous flight. Tracks flight data.
Giant Power Li-Po battery	Power source for the entire vehicle. Capable of 5000 milliamp-hours.
FrSky Taranis Radio System	Controller and transmitter that interfaces with the receiver. Communicates with the drone through Radio Frequency waves.
Receiver	Converts Radio Frequency waves from the transmitter into electrical signals for the Pixhawk.

meters before stalling due to being vertical and suffering rapid unscheduled disassembly of auxiliary structural parts. The 3D printed wings and tail, however, were unharmed despite taking the entire initial crash force, showing the robustness of the design. During the second test flight, the vehicle encountered an obstacle on the runway and required a new propeller. The third flight was the most successful, in which the automatic stabilisation provided by the Pixhawk controller was enabled and the vehicle achieved takeoff then, as seen in figure 12, demonstrated the ability to turn by employing the roll capabilities granted by the ailerons, then executed a controlled landing unharmed.

In the fourth test flight, during landing, a mis-input occurred and the vehicle suffered a small tear in the 3D printed tailpiece as the result of a crash as seen in 8 (a). The piece was able to be reprinted within an hour, pictured in figure 8 (b), and replaced within ten minutes, showcasing the completion of the objective to design for ease of repair. These tests show the success of the project, having accomplished the validation of the flight kits functionality, as well as proving ease of repair from real world damage, and proving automation to be

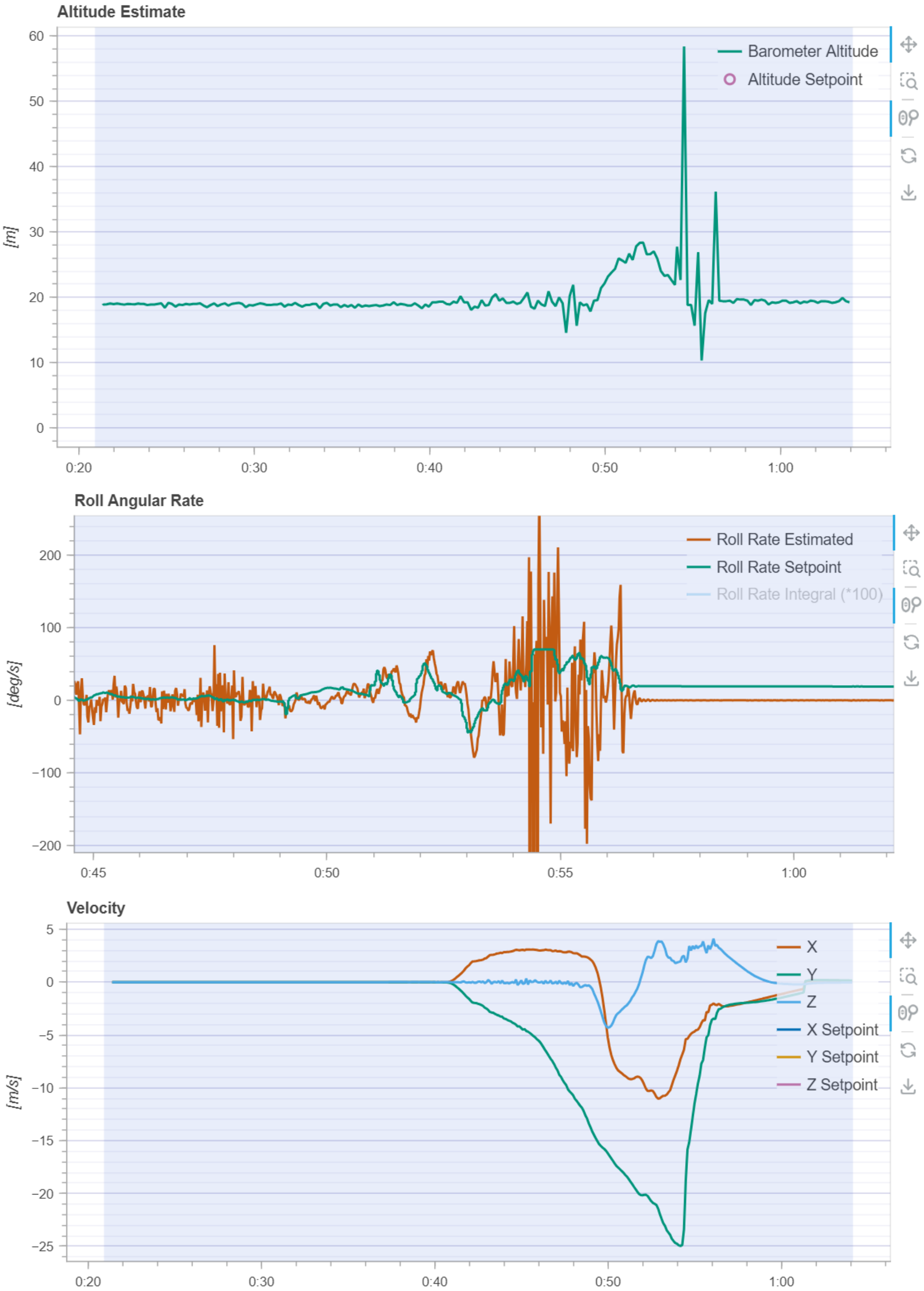

Figure 11 (a) Graph of Altitude in meters vs. time in seconds. (b) Graph of Roll angle in degrees vs. time in seconds. (c) Graph of velocity in meters per second. All from test flight 3, taken from Pixhawk flight logs.

possible by way of employing the Pixhawk controller's built in stabilisation routine.

4.1.1 Air Capabilities

During test flights, the Pixhawk module was recording data from it's sensors to a micro SD card that could then be extracted. However, due to conditions around testing, some instruments could not be properly tuned. The vehicle reached a barometrically measured altitude of 58 meters, starting from 20 meters above sea level, which is incorrect. Eye-witness accounts during testing set the maximum height reached at $\sim$4 meters. This was done not due to any inability to reach greater altitudes, but because the robustness of the design was not yet corroborated and failure at higher altitudes may have caused injury to

Figure 12 Demonstration of the vehicle's ability to turn in air using ailerons. Image from test flight 3.

Figure 13 The vehicle at the apex of it's vertical climb, having stalled but not yet started falling. Image from test flight 1.

Figure 14 The vehicle showcasing a smooth liftoff from the ground, thanks to automatic stabilisation from the Pixhawk controller. Image from test flight 4.

bystanders. A maximum speed of 90 kilometers per hour was recorded, which cannot be corroborated, however it is known the vehicle reached speeds higher than 35 kilometers per hour, the stall speed, as it achieved liftoff. The vehicle demonstrated the ability to execute a controlled turn at a bank angle of 41°and a speed of 70°per second, and is estimated to be able to fly for 17 minutes 30 seconds on one charge of the battery as determined below.

4.1.2 Water Capabilities

The vehicle was not able to be tested on water, largely due to the lack of waterproofing exhibited by the modified boat base. However, as previously calculated, the stall speed of the vehicle is 35 kilometers per hour, and the boat has a maximum manufacturer defined speed of 70 kilometers per hour unmodified. Due to the fact the vehicle can achieve liftoff with the plane propellers alone on a grassy surface, it can be assumed that takeoff from a reasonably calm body of water, such as those it is intended for, would be possible.

4.1.3 Battery Life Estimates

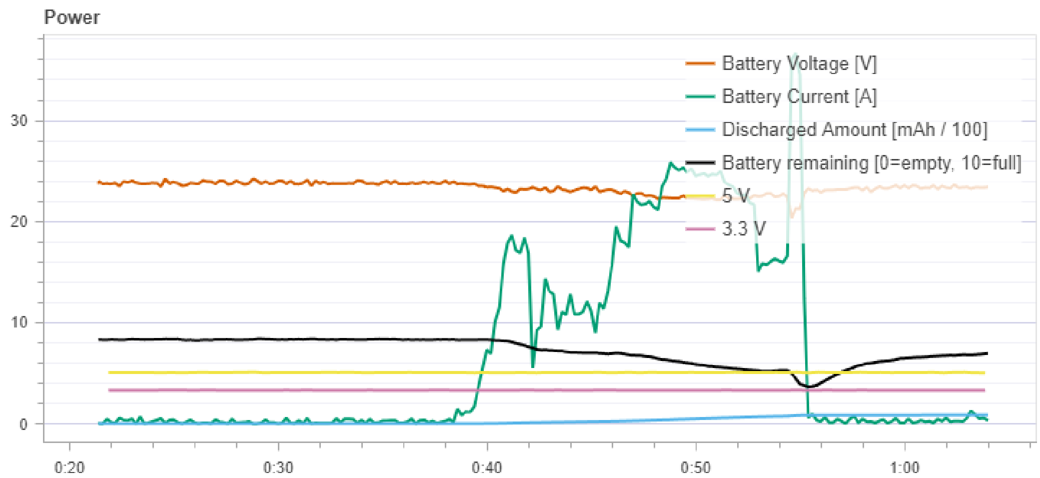

Figure 15 Battery life graph obtained from Pixhawk during test flight four.

The plot in Figure 15 shows multiple measurements of the vehicle battery during the fourth flight, which produced the cleanest graphs. From this, the expected time the battery can power the two motors for can be obtained. As indicated by the graph, the motors started at 38 seconds and stopped at 56 seconds. The "Battery remaining" graphed line is calculated by the voltage potential measured across the battery. As voltage varies under load, this results in a rough estimate that will not give an accurate estimate of battery life, even taking into account the voltage variations, as shown by the line on the graph decreasing at irregular intervals and even increasing when the battery has no load. This leaves the options of using the current over time directly to calculate the Ampere-hour loss, or using the "Discharged Amount" graph line, measured in Ampere-hours. These methods should produce the same result. Firstly, by converting the Ulog file to comma separated values, the exact numbers of the graph can be revealed. From the reading of discharged amount, the reading of 4.8 milliApmere-hours per second is obtained, and as the battery is 5000 milliAmpere-hours, as specified in table 2, the battery life can be determined as 17 minutes 30 seconds, assuming the vehicle is flown in the same manner the entire time. While this assumption will not hold true in a long range flight such as the vehicles intended purpose, it can give a good estimate and reveal that for real-world applications, battery life would need to be increased, or a way to recharge battery during mission obtained.

5. Discussion & Conclusions

This project introduced a method of creating 3D printed wings for fixed-wing multi-modal UAVs. The technique involves printing specialty PLA with specific slicer settings to create lightweight, structurally sound airfoil wing sections that include functional ailerons and can be reinforced with rods or tubing. Such a design can be altered for any number of requirements and scenarios, and be both created and repaired cheaper than commercially available equivalent products. An electronic system was proposed for future automation, and calculations were provided for possible changes to requirements in other scenarios. The wing design and electronic system tests were detailed and discussed, and the wing design was found to be a viable option for fixed wing UAV construction while the electronic system was proven to be capable of full automation with few required changes. These results show potential for development into a fully functional multi-modal unmanned vehicle capable of air travel and water landings for the purpose of water testing or similar activities, such as logistical work to remote areas where a regular fixed wing drone may be unable to land. The prototype met all the requirements within the scope set at the genesis of the project by consisting of a working flight kit that can be attached to any reasonable vehicle platform, being easy to maintain, modify, and repair, and by satisfactory performance in real-world testing. The report met the objectives of describing techniques for construction and alteration of the prototype, and validating by discussion the automation and water faring performance possibilities. The broader implications of this work on the sub-field of multi-modal unmanned vehicles includes the ability to easily build on this work due to the adaptable nature of the design to create lightweight, aerodynamic structures for any possible requirements such as structurally redundant additions to aerial vehicles to reduce drag. The project serves as the foundation for further research into sea-air multi-modal travel, including the possibility of full autonomy and large-scale conservation or exploration applications.

6. Suggestions for Future Work

Possible future direction for the project includes modifying the wings for mounting on a more effective boat platform, such as that detailed in New Dexterity's paper on a 3D printed speedboat [1], and waterproofing the electronics, which should be trivial with greater interior space allowed by a larger platform. Also discussed was the possibility of allowing rotation of the wings downwards, so that the wingtips are in line with vehicles waterline when it is on the waters surface, to act as outriggers to compensate for the higher centre of gravity caused by the high wing mounting. A system could be designed for differential steering, as the current hardware does not allow for that. However, the obvious first step is integrating autonomy into the design, which while proven to be possible during testing, could be enhanced by a computer vision system such as that in NTNU's fixed-wing UAV [4]. Another possible direction is the optimisation of weight to allow for more batteries and therefore a larger range, or integrating a system for recharging while on-mission.

References

[1] P. Mitchell, R. O'Brien, and M. Liarokapis, "On the development of waterjet-powered robotic speedboats: An open-source, low-cost platform for education and research," in *2022 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR).*

IEEE, 2022, pp. 153–159.

[2] F. Sotelo-Torres, L. Alvarez, and R. Roberts, "An unmanned surface vehiclex (usv): Development of an autonomous boat with a sensor integration system for bathymetric surveys," *Sensors*, vol. 23, p. 4420, 04 2023.

[3] J. Liang, J. Buzzatto, and M. Liarokapis, "A tailsitter uav based on bioinspired, tendon-driven, shape-morphing wings with aerofoil-shaped artificial feathers," 08 2023.

[4] S. G. Mathisen, F. S. Leira, H. H. Helgesen, K. Gryte, and T. A. Johansen, "Autonomous ballistic airdrop of objects from a small fixed-wing unmanned aerial vehicle," *Auton. Robots*, vol. 44, no. 5, pp. 859–875, may 2020. [Online]. Available: https://doi.org/10.1007/s10514-020-09902-3

[5] R. Zufferey, A. O. Ancel, C. Raposo, S. F. Armanini, A. Farinha, R. Siddall, I. Berasaluce, H. Zhu, and M. Kovac, "Sailmav: Design and implementation of a novel multi-modal flying sailing robot," *IEEE Robotics and Automation Letters*, vol. 4, no. 3, pp. 2894–2901, 2019.

[6] Y. Chen, H. Wang, E. F. Helbling, N. T. Jafferis, R. Zufferey, A. Ong, K. Ma, N. Gravish, P. Chirarattananon, M. Kovac, and R. J. Wood, "A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot," *Science Robotics*, vol. 2, no. 11, p. eaao5619, 2017. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.aao5619

[7] A. Mckinnon, "The possible impact of 3d printing and drones on last-mile logistics: An exploratory study," *Built Environment*, vol. 42, pp. 617–629, 12 2016.

[8] S. Wich, M. Hudson, H. Andrianandrasana, and S. Longmore, *Drones for conservation*, 08 2021, pp. 35–52.

[9] B. Berman, "3-d printing:the new industrial revolution," *Business Horizons*, vol. 55, 03 2012.

[10] T. Rayna and L. Striukova, "From rapid prototyping to home fabrication: How 3d printing is changing business model innovation," *Technological Forecasting and Social Change*, vol. 102, pp. 214–224, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0040162515002425

[11] M. U. ST Larned, T Snelder and G. McBride, "Water quality in new zealand rivers: current state and trends," *New Zealand Journal of Marine and Freshwater Research*, vol. 50, no. 3, pp. 389–417, 2016. [Online]. Available: https://doi.org/10.1080/00288330.2016.1150309

[12] R. Staniszewski, B. Messyasz, P. Dabrowski, P. Burdziakowski, and M. Spychala, "Recent issues and challenges in the study of inland waters," *Water*, vol. 16, no. 9, 2024. [Online]. Available: https://www.mdpi.com/2073-4441/16/9/1216

[13] J. Alves and N. Cruz, "Fast - an autonomous sailing platform for oceanographic missions," in *OCEANS 2008*, 10 2008, pp. 1 – 7.

[14] N. A. Cruz and A. C. Matos, "The mares auv, a modular autonomous robot for environment sampling," in *OCEANS 2008*, 2008, pp. 1–6.

[15] W. Jo, Y. Hoashi, L. L. Paredes Aguilar, M. Postigo-Malaga, J. M. Garcia-Bravo, and B.-C. Min, "A low-cost and small usv platform for water quality monitoring," *HardwareX*, vol. 6, p. e00076, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2468067219300367

[16] S. M. Hong, K. S. Nam, J. D. Ryu, D. G. Lee, and K. N. Ha, "Development and field test of unmanned marine vehicle (usv/uuv) with cable," *IEEE Access*, vol. 8, pp. 193 347–193 355, 2020.

[17] O. M. Cliff, D. L. Saunders, and R. Fitch, "Robotic ecology: Tracking small dynamic animals with an autonomous aerial vehicle," *Science Robotics*, vol. 3, no. 23, p. eaat8409, 2018. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.aat8409

[18] L. Meier, P. Tanskanen, L. Heng, G. H. Lee, F. Fraundorfer, and M. Pollefeys, "Pixhawk: A micro aerial vehicle design for autonomous flight using onboard computer vision." *Auton Robot*, 2012.

[19] C. Sampedro, A. Rodriguez-Ramos, H. Bavle, A. Carrio, P. de la Puente, and P. Campoy, "A fully-autonomous aerial robot for search and rescue applications in indoor environments using learning-based techniques," *Journal of Intelligent & Robotic Systems*, vol. 95, no. 2, pp. 601–627, Aug. 2019. [Online]. Available: https://doi.org/10.1007/s10846-018-0898-1

[20] L. P. Koh and S. A. Wich, "Dawn of drone ecology: Low-cost autonomous aerial vehicles for conservation," *Tropical Conservation Science*, vol. 5, no. 2, pp. 121–132, 2012. [Online]. Available: https://doi.org/10.1177/194008291200500202

[21] D. Scholz, "Aircraft design," Hamburg University of Applied Sciences, 2015, lecture Notes.

[22] T. Stanton, "How i designed a 3d printed wing," 2022. [Online]. Available: https://www.youtube.com/watch?v=QJjhMan6T_E