DEVELOPING A LOW COST FIXED-WING UNCREWED AERIAL VEHICLE FOR ATMOSPHERIC SENSING

A THESIS SUBMITTED FOR PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

GLOBAL ENVIRONMENTAL SCIENCE

AUGUST 2022

By
Erickson D. Shull

Thesis Adviser

Alison D. Nugent

I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISER

Alison Nugent

Alison D. Nugent
Department of Atmospheric Sciences

PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank Dr. Alison Nugent for her wonderful guidance and support through this project. Katie Ackerman, Mya Sears, Tianqi Zuo for feedback and advice; Shaun, Han, Jahsten, Nyk as well as many friends in G.E.S. for encouragement and advice; Mealani for her kindness and affection; and for Mom, John, Dad, Charles, Sachelle, and Noah for helping guide me down this path.

ABSTRACT

Within the earth and atmospheric science disciplines, there has been a growing need for low-cost uncrewed aerial vehicles (UAV) and their associated instrumentation. UAVs have the ability to facilitate both in-situ and remote sensing measurements in the lower atmosphere without the cost and complexity of a crewed aircraft. This design thesis tackles the challenge of creating a low-cost airframe that does not require significant experience to build, maintain, or operate. All materials needed to build the airframe can be found at local hardware stores including expanded polystyrene, aluminum bar stock, and corrugated plastic. Five airframe designs were tested for their effectiveness given a number of set requirements including being able to continuously fly for 15 minutes, reach 30 kilometers per hour (kph) airspeed, and report usable temperature, pressure, and position data from an onboard suite of sensors. The final airframe design is found to be effective at flying at speeds between 5-45 kph with temperature, pressure, and position data continuously logged onto an onboard SD card. The design is also particularly effective because of its low cost to operate, ability to fly with a wide variety of sensors, and effective range. The airframe is useful for earth and atmospheric science research purposes and provides new affordable opportunities for scientific measurement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D ………………………………………………….. Three Dimensional

AGL …………………………………………….Above Ground Level

ESC…………………………………………..… Electronic Speed Controller

FAA…………………………………………..…Federal Aviation Administration

ft………………………………..…..……..Feet

GPS…………………………………………..…Global Positioning System

GHz……………………………………………Gigahertz

Hz……………………………………….…..Hertz

KF……………………………………….…..Kline-Fogleman

kg………………………………………..……Kilogram

km/h…………………………………………... Kilometer Per Hour

kV……………………………………….….. Kilovolt

m……………………………………….…Meters

mAh……………………………………………Milliamp hour

MH60…………………………………………..Martin-Hepperle 60

MHz……………………………………………Megahertz

Mk ……………………………………….… Mark

UAS…………………………………………… Uncrewed Aerial System

UAV…………………………………………… Uncrewed Aerial Vehicle

Chapter 1

INTRODUCTION

1.1 Importance of Uncrewed Aerial Vehicles

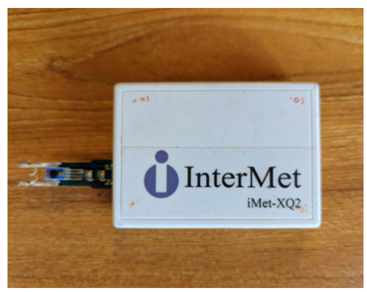
Uncrewed aerial vehicles (UAV) have become an important tool in atmospheric and earth sensing due to their ease of use, cost of operation, transportability, and ability to perform a multitude of roles based on their sensor suite. Even without the Federal Aviation Administration (FAA) authorization, UAVs are allowed to fly under 400 ft above ground level (AGL) which aircraft and helicopters are not usually able to access. Due to these attributes, both rotary and fixed-wing uncrewed aerial vehicles have become increasingly popular for data collection. Building a low-cost, easy to construct fixed-wing aircraft gives researchers the ability to cover large areas quickly and with minimal effort while also creating a platform that is easily modified to fit specific mission parameters.

Uncrewed aerial vehicles (UAV) are utilized in many aspects of earth and atmospheric sensing as UAVs are easily transportable, able to perform a multitude of roles based on the sensor suite, inexpensive to operate, and able to fly under 400 ft (~120 m) AGL. Currently, Dr. Alison Nugent's lab in the Atmospheric Sciences department at the University of Hawaiʻi at Mānoa within the School of Ocean and Earth Science and Technology utilizes a Yuneec Typhoon H multirotor (Figure 1) which is a hexacopter design using 6 motors to produce lift. Due to the inherent use of multiple motors to propel and keep the craft aloft, multirotor UAVs cannot efficiently stay airborne for long periods of time. This also means that fast movements with a multirotor aircraft will consume large amounts of power thereby limiting flight time. Because of this design limitation, the current multirotor used by Dr. Nugent's research group can only stay aloft for approximately 15 minutes at a time. However, by using a fixed-wing aircraft design utilizing lifting surfaces of the wing and a single motor, this issue can be rectified. It would also allow for efficient locomotion and achieve the goal of at least 15 minutes of flight time while obtaining speeds of at least 30 kph.

a)

(Yuneec Typhoon H, 2022)

b)



c)

Figure 1: a) Yuneec Typhoon H Hexacopter, b) InterMet iMet-XQ2 UAS sensor, c) Kualoa Beach Park.

1.2 Multirotor UAV

Multirotor UAVs, such as quadcopter drones, utilize two or more vertical-facing motors and their subsequent propellers to produce lift (Figure 4). Multirotor UAVs also need an onboard flight computer to calculate motor input so that the vehicle can stay in level flight or produce other maneuvers, as they are inherently unstable otherwise. Due to this, multirotor UAVs typically cost more to produce than similarly sized fixed-wing

UAVs. Multirotor UAVs have the advantage of being able to vertically take off and land which makes their design suitable for areas where ground space is limited. Rotary UAVs also tend to have a shorter learning curve when it comes to controlling the vehicle. The disadvantages associated with multirotor UAVs have to do with range and flight speed. The range is a function of flight speed whereby the faster the vehicle flies the less range it is capable of. When using multiple motors to produce lift, battery consumption becomes an issue. There is also no glide slope when a multirotor has a malfunctioning electronic speed controller or motor failure. The glide slope is the path that an aircraft takes when no throttle is applied. Thus, it is important to have a glide slope because of its use in emergency landings, as a longer glide slope allows more time for the pilot to find a safe place to land.

(*DJI Mini 2*, 2022), (*DJI Phantom 4 pro V2.0*, 2021), (*Parrot Bebop 2 Drone*, 2022)

Figure 2: Example of popular multirotor drones on the market

1.3 Fixed-Wing UAV

The term “fixed-wing” refers to aircraft with fixed horizontal surfaces that are capable of producing lift such as the wings of a plane. Depending on the design, fixed-wing aircraft do not necessarily need an onboard computer to create a level flight. However, one such as a Pixhawk 2.4.1 can be used to help the operator by keeping smooth level flight through utilizing the onboard accelerometers to counteract turbulence without input from the pilot. The advantages of using a fixed-wing aircraft include increased range requirements and higher achieved ground speeds which subsequently allow for larger area coverage. Range increases with fixed-wing UAVs due to the efficiency that its wings allow in flight. Unlike a multirotor, a plane does not require the constant use of the motor to stay aloft. A fixed-wing aircraft also has higher average ground speeds compared to a multirotor as airspeed must be maintained in order to keep the aircraft aloft.

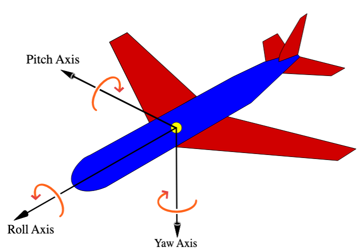
(*Swan K1 Pro*, 2022), (*2015 Skywalker 1680*, 2017), (*ZOHD Talon GT Rebel 1000mm*, 2020), (*HeeWing T1 Ranger*, 2022)

Figure 3: Example of some of the most popular fixed-wing UAVs on the market

1.5 Fixed Wing Aircraft Control Surfaces and Terminology

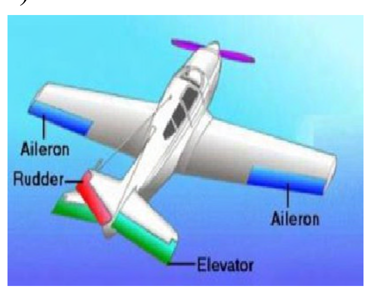
Fixed-wing aircraft have multiple control surfaces that are used to manipulate aircraft in three dimensions (3D) called pitch, roll, and yaw (Figure 4a). This manipulation is called the aircraft's principal axes. The first of these axes is referred to as pitch, a rotation about an aircraft's lateral axis, controlled by the elevator (Figure 4b) on a traditional fixed-wing aircraft. Next, roll refers to the rotation about an aircraft's longitudinal axis, traditionally manipulated by a control surface on opposite ends of the aircraft's wing called the ailerons (Figure 4b). Lastly, yaw is a rotation around an aircraft's vertical axis traditionally controlled by the rudder (Figure 4b). Yaw can also be controlled by differentially speeding up or slowing down opposing motors on a multi engine aircraft (figure 4c).

a)



(*Aircraft Principal Axes*, 2022)

b)



(All about Aviation, 2020)

c)

(Bob Report Staff, 2011)

Figure 4: a) Pitch, roll, and yaw axis manipulation, b) Control surfaces of a fixed wing aircraft and c): Beech King Air 350, an example of a twin engine fixed wing aircraft.

1.7 Goal of Project

Multirotor UAVs are able to use less space for take-off and landing and hover in place. However, their cost, achievable top speed, flight duration, and range requirements create limitations to their mission parameters. The goal of this project is to produce a low-cost, fixed-wing aircraft that is able to reach speeds of at least 30 km/h, be aloft for at least 15 minutes, and use its onboard sensor suite to log atmospheric base parameters and calculate lapse rate. It is expected that during the atmospheric observations portion of this project lapse rates will be near the dry adiabatic lapse rate of 9.8℃/ km. To provide context for this design project, chapter 2 will include an overview of the design and methods. Chapter 3 will include results on aircraft iterations and measurements taken. Chapter 4 will discuss problems that arose during the building stage as well as talk about the process of finding an ideal sampling site and what was found during the sampling. Chapter 5 will conclude this design project with final remarks on the overall project goal, aircraft performance, future iterations, and possible research opportunities this aircraft can provide.

Chapter 2

DESIGN AND METHODS

In order to show the viability of a low-cost UAV, the materials for the construction of the airframe were gathered from a local home improvement center and were built in a simple, cost-effective manner.

2.1 Fuselage Methodology

The fuselage was constructed with the following requirements in mind: interior cargo space needed for flight electronics and other equipment, low weight for increased payload capacity and flight times, minimal costs to keep the project accessible and within design parameters, low complexity to aid the previous requirement and be easily replicable for others, and adequate strength to withstand hard landings.

In constructing the final iteration of the aircraft, corrugated plastic was used. This was for two purposes: (1) Corrugated plastic has a higher yield strength than similar weight single wall plastic (Jiang et al., 2020). (2) Corrugated plastic can be cut as one monolithic piece and folded to create an elongated box. This means there are no separate panels that could break away in a crash. One bulkhead is epoxied into the center of the body to increase rigidity in the center of the fuselage. Ultimately, the folded corrugated plastic design allowed for a good balance between strength, weight, cost, and complexity.

2.2 Wing Methodology

The wing methodology for the final iteration had to take weight, strength, and complexity into consideration as well. It was found after a few prototypes that extruded polystyrene was a great material candidate, as its lightweight but high impact resistance meant that hard crashes were of little concern. The idea for using extruded polystyrene came from a video by Samm Sheperd where he built a simple hot wire cutter to cut expanded polystyrene. However, this is easily done with extruded polystyrene as well (Shepherd, 2016). Once the polystyrene was cut, the wing was covered with packing tape, giving in more rigidity. The airfoil chosen for this hotwire method is called a Clark Y. The Clark Y airfoil is a simple flat bottom airfoil design that was developed in 1922 by Virginius E. Clark. This Airfoil is popular among many model aircraft builders due to its ease of construction and forgiving stall characteristics (Marchman III & Werme, 1987). The Clark Y airfoil is used in the Mk IV-VI wings. Overall, this method is not the simplest construction method when compared to a KF airfoil seen on the flying wing prototype. However, the material is easily attainable and allows for light yet durable wings.

2.3 Data Transmission

Data transmission is the process of sending information to or from the aircraft. This is important for controlling the aircraft as well as getting crucial video, battery, and GPS data back to the operator. For the aircraft controls, the operator uses a FrSky Taranis QX7 2.4GHz controller connecting to a FrSky R8 pro receiver on the aircraft which provides a theoretical range of approximately 2 km. To transmit video data, a RunCam 2 is connected to a 5.8GHz ImmersionRC 200mW audio/video transmitter, which then transmits back to a ground station monitor. A Pixhawk 2.4.8 is used onboard, transmitting on 900mHz frequency. It is important to note that all these systems are running on different frequencies so as to not interfere with one another.

2.4 Remote Control Electronics

On the aircraft, there are specific electronics that are used to communicate with the user while controlling the principal axes and managing motor speed. To allow the user to control the aircraft, a remote controller or transmitter and receiver are used (Figure 9). The transmitter and receiver work in a 2.4 GHz frequency which has a theoretical range of 2 km. In order to manipulate control surfaces, 9 gram servo motors (Figure 10) were used. These strike a good balance between servo weight and usable torque which is around 1.5 kg. To propel the aircraft, a brushless 1100 Kv motor was used (Figure 11). Brushless means there are no carbon brushes touching the stator of the motor to power the windings. Instead, three phase alternating current (AC) is used to turn on electromagnets in a specific order to turn the motor. Kv is a measure of the motor's rotational speed divided by the nominal voltage applied (Kv = $\frac{RPM}{V}$) . This is a common metric which hobby motors are measured and marketed by. To power the motor and servos an 11.1 volt, a 2200mAh lithium polymer battery (Figure 12) connected to a 40 amp ESC (Electronic Speed Controller) is used. The ESC (Figure 13) has two purposes, the first of which is to turn the direct current (DC) power from the battery and convert it into three phase alternating current. The second purpose of the ESC is to step the 11.1

volts from the battery down to 5 volts DC which are subsequently used to power the 9 gram servos and receiver.

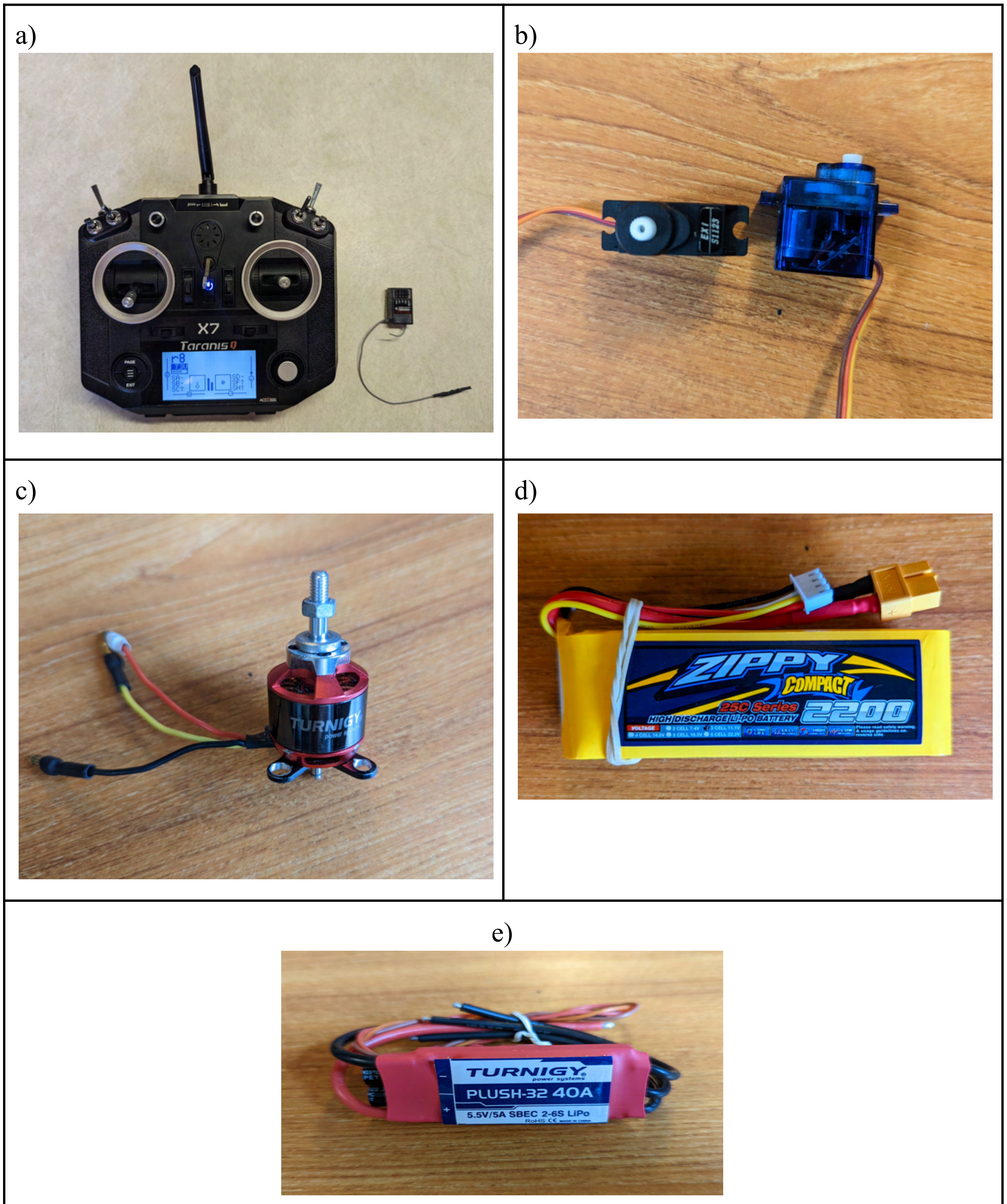


Figure 5: Example of a) a transmitter and receiver, b) 9 gram servo motors, c) a 1100KV motor, d) an 11.1V 2200mAh lithium polymer battery, and e) a 40 amp Electronic Speed Controller.

2.5 Manufacturing Methods

Hotwire cutting:

Hotwire cutting is a process in which a nickel-chromium wire has a constant direct current power flow through it. By doing so, the wire will heat up, allowing it to cut through objects such as foam. This technique is used on all of the extruded polystyrene wings, as it allows the user to cut fluid curved lines with the use of a template guide that can be affixed to the piece of foam that is being cut. Although it is not the easiest method of constructing wings, hot wire cutting was chosen over other construction methods due to its ability to produce lightweight, precise airfoils.

2.6 Sensor Suite

The sensor suite onboard the aircraft consists of an iMet XQ2 which logs pressure, temperature, humidity, and GPS data. The XQ2 is placed on the top of the wing for the most accurate measurements. A Pixhawk 2.4.8 is housed inside the body of the aircraft and carries a magnetometer, barometer, accelerometer, lithium battery monitor, and a GPS module to send back to a ground station. The XQ2 and Pixhawk both log data at a rate of 1Hz.

2.7 Location

Testing the plane took place during the COVID-19 pandemic which meant that the testing location and data collection area were in two different environments. Testing took place on the island of Maui, primarily below PoliPoli State park where the landowner had given verbal permission to use the cattle grazing land as a place to test the aircraft. This land was a wide-open sloped area with knee-high grass which made for forgiving landings in the event of a crash. For the data collection area, Kualoa Beach Park was chosen for its low-density foot traffic, large open grass area for landings, and calm atmospheric conditions leading to an ideal preliminary data collection.

2.8 Calculating Atmospheric Observations

The data from the iMet XQ2 was taken at 1 hertz and then inputted into Matlab where 3d plots were created. In order to calculate altitude, the following equation was used:

$$P(h) = P_0 e^{\frac{-gM(h-h_0)}{RT}} \quad \text{(Equation 1)}$$

where P is the pressure at altitude h, P_0 is the starting pressure, g is gravity, M is the molar mass of air, h is height, R is the universal gas constant, and T is the temperature at altitude. The base pressure that is needed for the equation is taken from a Kestrel 5500. Measurements were taken once per week, typically on Friday mornings between February 15, 2022, and March 18, 2022.

In parallel with calculating height via pressure, lapse rate was calculated. The lapse rate is the rate at which a particle of air is brought into the atmosphere. The lapse rate calculation is as follows:

$$\lambda = \frac{T_2 - T_1}{h_2 - h_1} \quad \text{(Equation 2)}$$

where λ is the lapse rate, *T* is the temperature, and *h* is altitude. The lapse rate is measured in $°C/km$.

Chapter 3

RESULTS

The above methodology for aircraft building was used for a number of aircraft and wing designs. Each aircraft, wing, and body design tested built upon the drawbacks of previous designs. Results are provided in five parts: (1) aircraft body iterations, (2) aircraft wing iterations, (3) final aircraft design, (4) field testing/ flight sampling, and (5) atmospheric observation.

3.1 Aircraft Body Iterations

EXP 1:

The EXP 1 was a flying wing design that utilized a Kline-Fogleman (KF) 1 airfoil on an 81.3 cm wing; it also had a rear-facing 1100 kV motor and one vertical stabilizer on each wingtip. This was the initial design prototype due to its ease of construction and lightweight airframe. However, the performance of the EXP 1 ultimately revealed its main flaw. The flying wing design was unstable at low speeds and had a tendency to stall at the wingtips. When a plane stalls at the wingtips, the plane has the tendency to aggressively roll. The aircraft also did not have sufficient space for all the electronics that needed to be installed on it and a resizing of the design would have made the aircraft cumbersome to transport. Overall the design of EXP 1 was flawed in the fact that it would be difficult for new pilots to handle and the limited room onboard made it difficult to hold necessary equipment. However, the rear-facing motor was a design element that showed promise in the fact that the motor would be less likely to be damaged in the event of a crash.

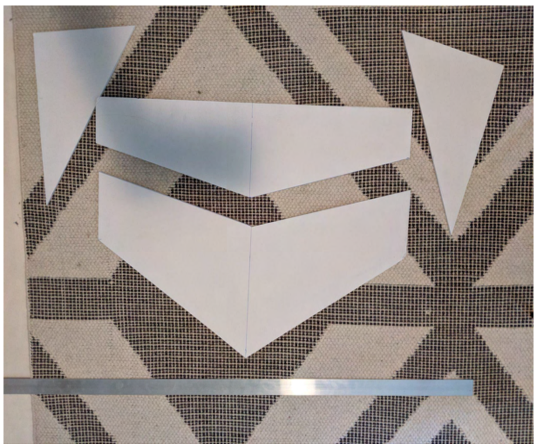
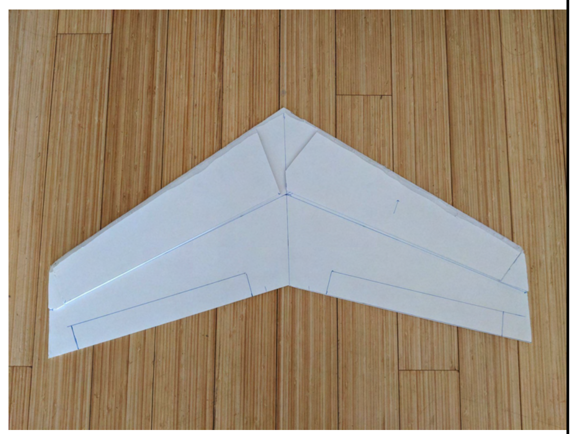
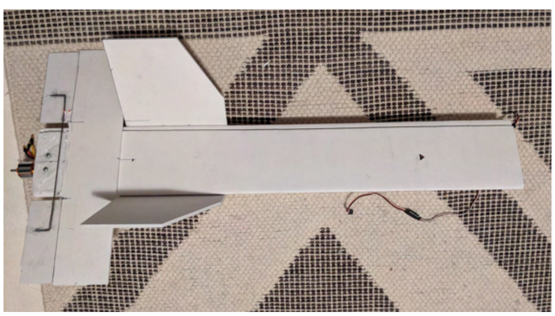
a)	b)
	

Figure 6: a) The EXP1 flying wing cut into its individual pieces b) EXP1 is fully assembled but without electronics.

Version 1:

The Version 1 airframe was a triangular 1m long foam board body open on both ends. The motor and twin vertical stabilizers were mounted on the rear of the body, with the wires running through the center to power the electronics and servos. The body was able to withstand hard landings as there were no service ports (which often lead to points of failure), but this created an issue of user serviceability because parts were difficult to access. The airframe was also heavy for its size with a weight of 654 g. Overall, the Version 1 body had promise, but weight needed to be reduced to make it a feasible design.

a)



b)

Figure 7: a) Version 1 body without a wing b) Version 1 body fully assembled.

Version 2:

The Version 2 airframe had the same triangular body as Version 1. However, it was reduced in length by 28 cm making the overall length of the body 72cm. The Version 2 body utilized two carbon fiber booms attached to the Mk II wing going to the tail. It is important to note that while the length reduction improved the problem with weight, user serviceability was still found to be lacking, as snaking wires through the body were difficult. This airframe was also still open in the front, allowing airflow over the electronics which was not ideal. Given these drawbacks and shortcomings, this design was retired and replaced with a new design with more space for servicing and improved safety for the electronics.

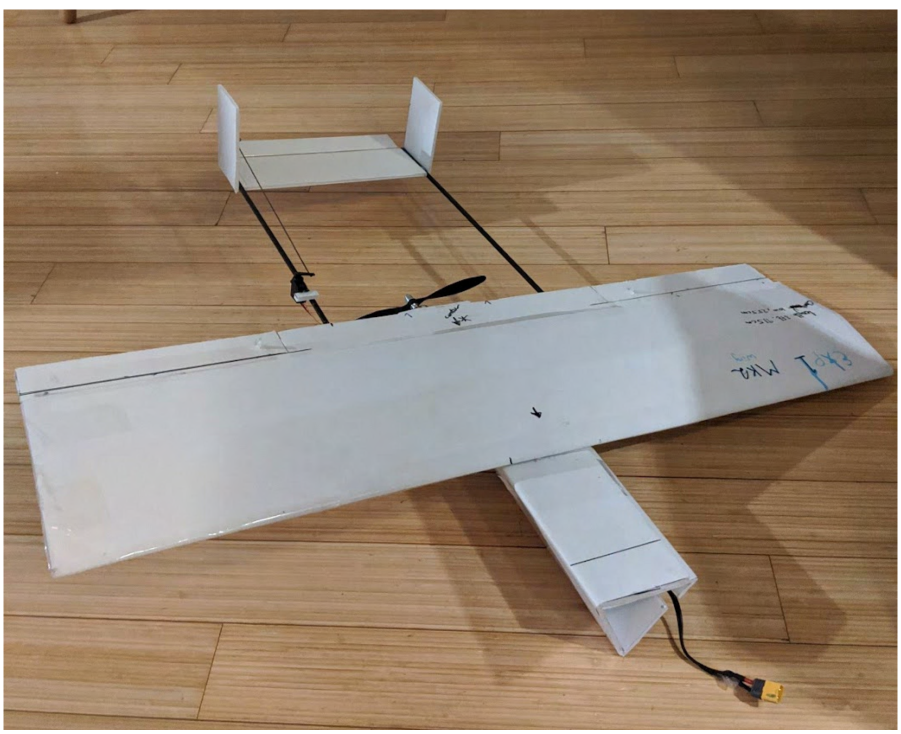
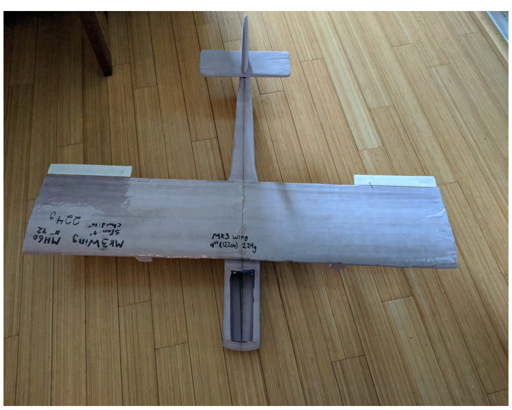


Figure 8: Version 2 body fully assembled with Mk II wing attached.

.

Version 3:

The version 3 airframe was a foam hotwire-cut body modeled after a Cessna 172 Skyhawk. It was the lightest airframe, weighing at 551 g and had a rectangular cut-out in the nose to house flight electronics and instruments. The tail section of the airframe was reinforced with a 3 mm carbon spar for rigidity. The Mk4 wing was designed in conjunction with this airframe in order to hold both the ESC and 1200 kV motors. During flight testing, the nose hit the ground and snapped at its battery housing area (Figure 9b). To fix this, two carbon spars were epoxied into the nose of the aircraft. The issue with this design was the cost, complexity, and time consumption. At the time of construction, the foam needed for the body cost around $43 for a 4x8 ft section. The complexity and time needed to complete the design were also not ideal, as crashes could easily take this aircraft out of commission. Thus it was deemed that a simple airframe was needed to preserve the goal of building an iteration that did not compromise on cost nor flexibility.

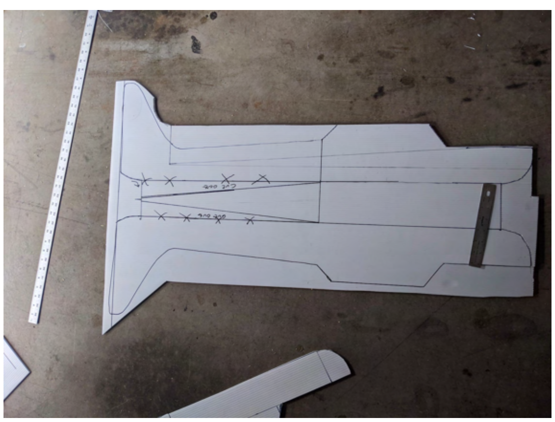
a) 

b) 

Figure 9: a) Version 3 body fully assembled with no electronics installed, b) Version 3 body getting carbon spars installed in the nose after crashing during testing.

Version 4:

The version 4 airframe is made of corrugated plastic and is similarly shaped to the version 3 airframe. Bulkheads were placed at approximately 4” increments and secured with epoxy. This airframe uses the Mk4 wing with two motors attached to it. While this airframe was able to fly, it was found that it was fairly tail heavy. To combat this, extra batteries were put into the nose to bring the center of gravity forward. The conventional small aircraft body style also meant that there was an unnecessary amount of wasted space in the tail section of the aircraft. To address the center of gravity issue and wasted space, one final design was tested.

a) 	b) 

c)

Figure 10: a) Version 4 body being mocked up, b) Version 4 body mostly constructed, c) Version 4 with Mk III wing flying past the operator.

Version 5:

The Version 5 airframe continued using corrugated plastic. However, cardboard was first used to mock up the design so as not to waste material. The Version 5 body was monolithic in design, meaning the whole body was cut at one time and bent in order to create its structure, similar to origami. This allowed for a very straightforward and strong structure that did not have unused space in the rear like Version 4. Interior cargo space also increased from Version 3 without losing structural integrity. Finally, the body of the aircraft was the lightest overall, weighing at 365g, and consequently allowing for higher payload weight capacities.

a)

b)

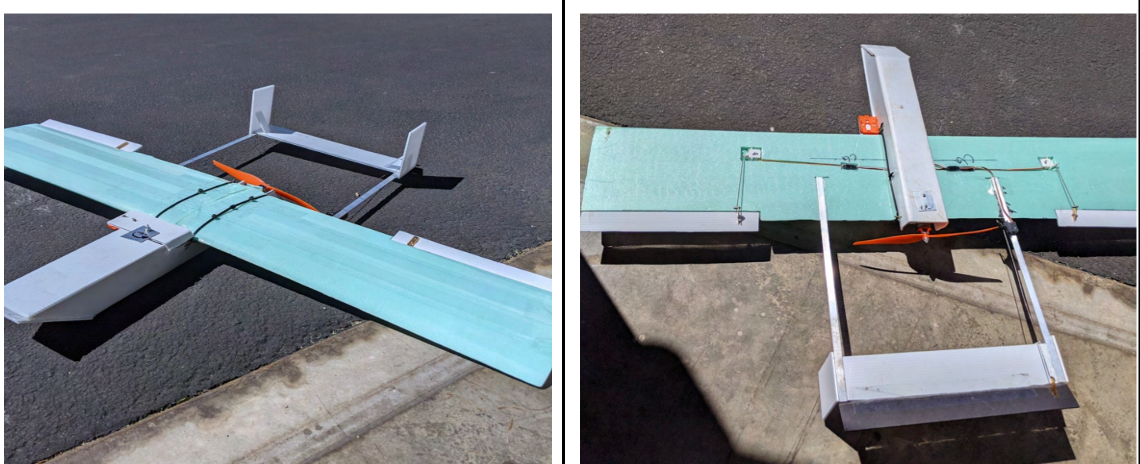


Figure 11: a) Version 5 body with MkV wing, b) Version 5 body underside.

3.2 Wing Iterations

Mark I wing:

The Mark I wing was a 71.5cm (28 in) all foam board wing that had two foam board spars running along its length. The spars gave the wing its airfoil as well as increased its rigidity. It had one servo that was used as a tie rod to move the two control surfaces on the wing. The Mk I wing weighed a total of 289 grams and was only used on the Version 1 body. Although this wing design was simple and inexpensive to produce, the weight of the foam board plus the imprecise nature of the airfoil led to a wing that did not generate enough lift for flight.

a) b)

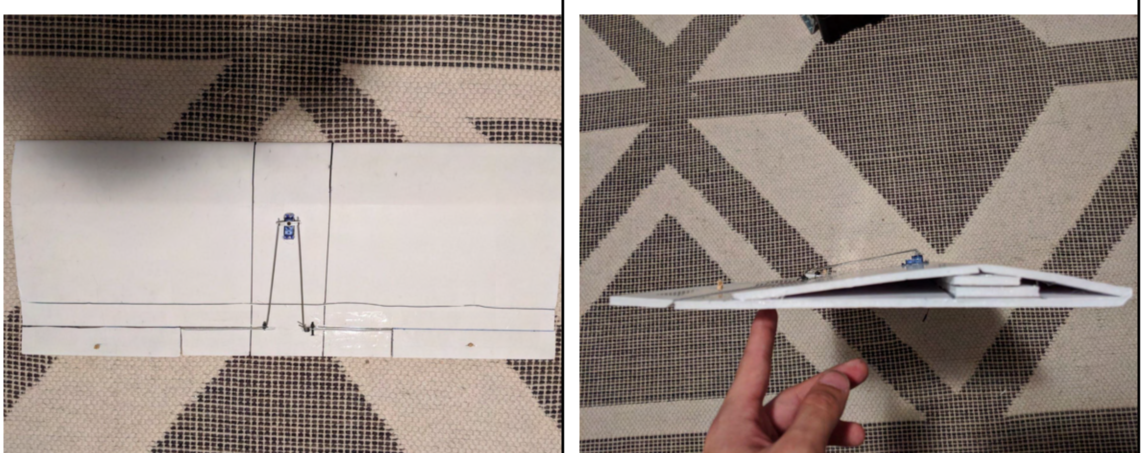
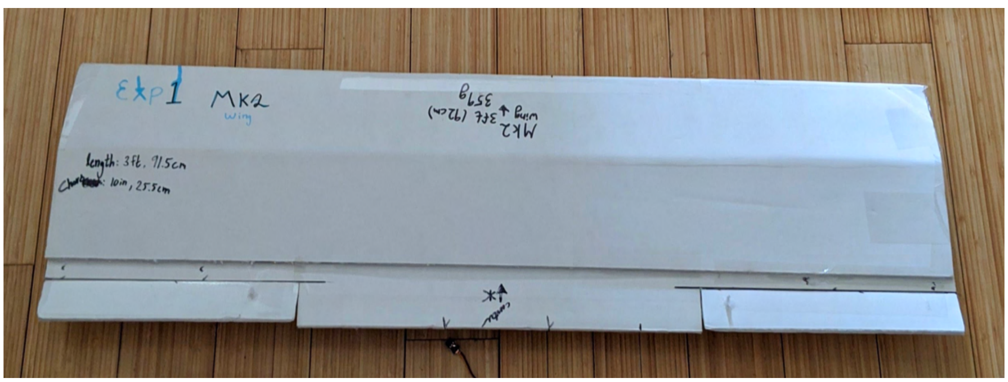


Figure 12: a) Top-down view of Mk I wing, b) Side profile of Mk I wing,

Mark II wing:

The Mark II was a 91.5 cm (3 ft) long foam board wing that used two 9 g servos to move the control surfaces on the wing. Additionally, the Mk II wing also used two foam board spars that spanned the length of the wing to create its airfoil. It weighed a total of 395 g, making it heavier than the Mk I wing. This design was iterated from the previous Mk I wing to have a larger lifting surface, as the previous design did not provide enough lift for the aircraft. Unfortunately though, this design also did not provide enough lift for sustained flight due to its weight and lack of a proper airfoil.

a)



b)

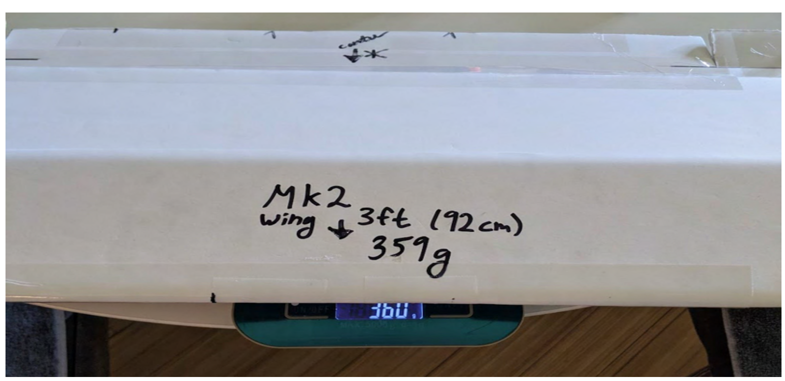


Figure 13: a) Top-Down view of Mk II wing, b) Mk II wing on scale

Mark III wing:

The Mark III wing was made of pink insulation foam (extruded polystyrene) that had been hotwire cut and reinforced with a carbon fiber rod that ran ¾ of the length of the wing. Once cut, it was covered in packing tape to increase its tensile strength. The Mk IV wing used a Martin-Hepperle 60 (MH 60) airfoil with a chord of 11” and 9% thickness. The Mk III wing was made in conjunction with the Version 3 body (and later the Version 4 body) and thus was specifically designed to have twin motors that were just far enough apart to clear the body. The ESCs were embedded into the foam wing to help keep a smooth bottom to the airfoil. The Mark III wing was later retired due to not needing two motors to propel the aircraft; they simply added unnecessary complexity and cost.

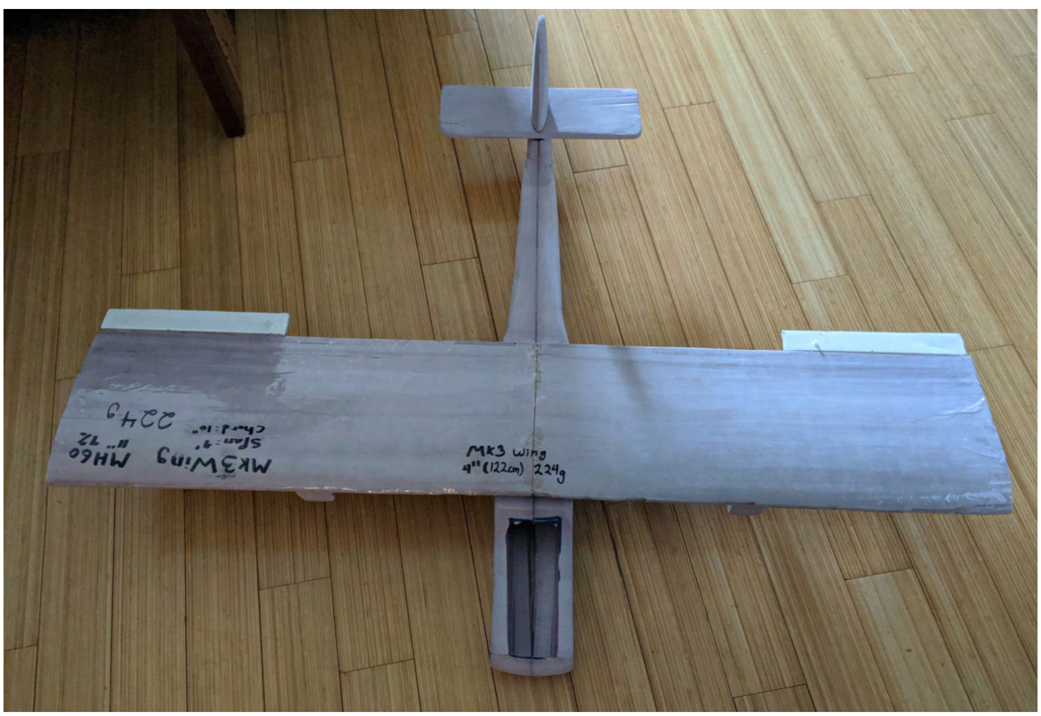


Figure 14: Mark III wing attached to aircraft body

Mark IV wing:

The Mark IV wing was also made of pink insulation foam (extruded polystyrene) that had been hot wire cut. It was also reinforced with a carbon rod through ¾ of the length of the wing and covered in packing tape to increase rigidity. The Mark IV wing utilized a Clark-Y airfoil with a 10” chord and an 11% thickness. The airfoil was changed from the MH-60 airfoil to the Clark-Y airfoil due to its flat bottom design, thus simplifying the construction process. Two 508 mm (20”) aluminum booms were placed at 178 mm (~ 7”) from the center of the wing. The booms were placed far enough apart to clear a 308 mm (12”) propeller and carry the aircraft's tail section. Servos were embedded into the wing to control the ailerons on either end of the wing.

Figure 15: Mark IV wing on the Version 5 body ready to be hand launched.

Mark V wing:

The Mark V wing was a slight iteration of the Mark IV wing. Similarly, it also used hot wire cut blue insulation foam (extruded polystyrene) reinforced with packing tape and a Clark-Y airfoil. The chord was changed from 254 mm (10”) to 228.6 mm (9”) and a 9.5% thickness. This was done in an effort to minimize drag. However, the overall flying characteristics did not change. Again, two 520 mm (20”) aluminum booms were placed on the wing to hold up the tail section. Overall the Mark V wing performed well when paired with the Version 5 body. Another reason the Mark IV was revised into the Mark V was due to the hot wire cutting process creating odd artifacts when the chord was shortened to 254mm. These artifacts would show up as ripples and grooves in the wing. While it could not be concluded why the artifacts showed up in the larger wing, shortening the chord cleaned up the hot wire cutting significantly.

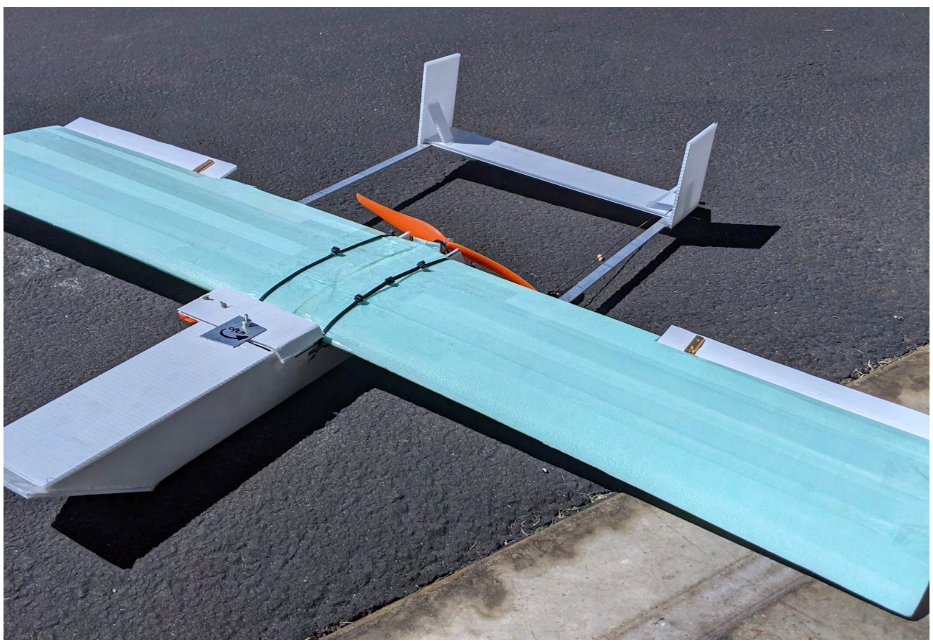


Figure 16: Fully assembled Mark V wing on the Version 5 body

Mark VI wing

The Mark VI was an experimental 2-meter (~ 6 ft) long Mk V wing that had a 3 mm carbon fiber rod that ran down the center to increase rigidity. Other than the length of the wing, the only other aspect that was changed was the size of the aileron being elongated in order to have enough roll authority with such large wings. The wings were placed onto the Version 5 body which was attached using aluminum right-angle brackets. The Mark VI wing did not handle well in even the calmest of weather conditions. The long wingspan meant that any slight breeze would push the whole aircraft. The carbon spar that ran through the wing was also found to be inadequate. Once the wing started creating lift, the wingtips would start to lift approximately 10 cm above the center of the wing. This would put immense strain on the wing to the point at which audible snapping could be heard from the ground. Lastly, the wing bending caused the right angle brackets holding the wing to the body to fail, leading to it crashing. Overall it was important to experiment with this design as it showed a point at which the design became impractical and dangerous.

a)

b)

Figure 17: a) The Mk VI wing flexing to the point that the body detached from the wing mid-flight, b) Crash of Version 5 body on the Mark VI wing. Note the body is still fully intact, and only minor repairs were needed on the tail.

3.3 Final Airframe Design

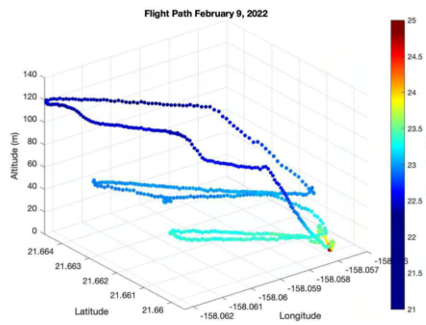
The final design of the aircraft consisted of the Version 5 body with the Mark V wing. The corrugated plastic body was the most durable of the designs, withstanding multiple hard landings and crashes. The simplicity and ease of construction also meant that, in the event of an unfixable crash, the aircraft could be easily repaired or replaced. The Mark V wing and its Clark-Y airfoil created a long gradual glide slope that was predictable for easy landings. The rear-facing motor on the V5 body mitigated the risk of slicing injuries from the propeller and kept the motor safe in the event of a crash. Lessons learned from the former body and wing designs instigated the need for a light but durable tail; the twin aluminum boom tail allowed for a high strength to weight ratio.

Figure 18: Final design (Version5 body, Mk V wing) at Kualoa Regional Park being hand launched

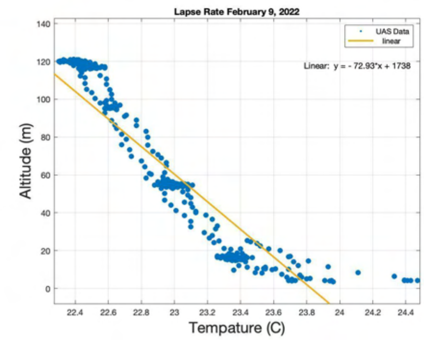
3.4 Atmospheric Observations

Using the final version of the aircraft with the Version 5 body and Mark V wing, atmospheric observations were taken at Kualoa Beach Park with the iMet XQ2 on Friday mornings from February 9, 2022 to March 25, 2022 starting around 7:30 - 8:00 am. Using the final aircraft to measure primary atmospheric parameters tested the aircraft's capabilities for data collection in future missions. Flying with the instruments in a controlled manner conducive to data collection for atmospheric observation was an important step for proof of concept. To ensure the atmospheric observations had sufficient accuracy for future research missions, lapse rate profiles were created with the data gathered from the iMet XQ2. This step helped to confirm that data collected by this aircraft was able to be manipulated for scientific purposes. Using this data, the following lapse rate profiles were produced.

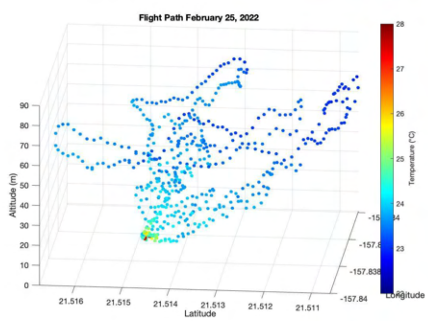
a)



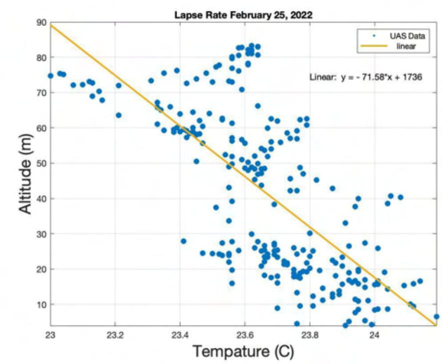
b)



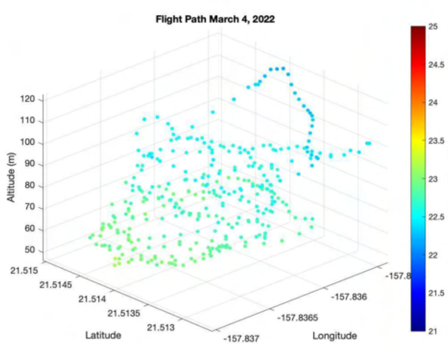
c)



d)



e)



f)

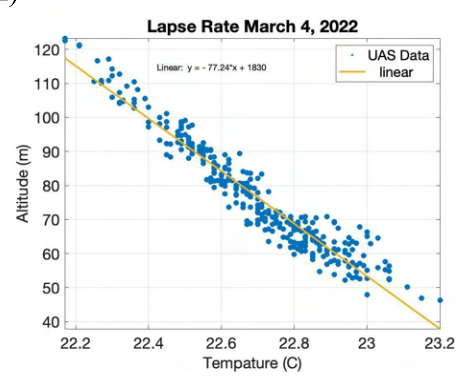


Figure 19: a) February 9th flight path b) February 9th lapse rate c)February 25th flight path d) February 25th lapse rate e) March 9th flight path f) March 9th lapse rate

The lapse rate is the rate at which temperature changes with altitude in the atmosphere. This is an important metric as lapse rate is a measure of the stability of the atmosphere. Using equation 2 (lapse rate calculation), it was found that there was a lapse rate of 12.8℃/km, 14℃/km, and 13.8℃/km respectively, measured by the aircraft on the three test flight days. All test flight days reported a lapse rate larger than 9.8℃/ ㎞, meaning the atmosphere was super-adiabatic (Nugent et al., 2019, Chapter 5: Atmospheric Stability). In comparison, a dry adiabatic lapse rate in the atmosphere would be around 9.8℃/ ㎞ (Nugent et al., 2019, Chapter 5: Atmospheric Stability)

Chapter 4

DISCUSSION

4.1 Problems Encountered and Addressed

Center of gravity: In many of the prototype airframes, it was found that the center of gravity was often behind the center of lift. This caused instability in flight, as the center of lift ultimately pushed the nose of the aircraft up (all while the center of gravity was maintained further back), leading to it dragging the tail down. This was rectified when either the tail portion of the plane was shortened or more weight was added to the nose of the aircraft in order to push the center of gravity toward the center of the aircraft.

Wing and motor set up: In some of the body versions, the aircraft took on a more traditional Cessna-esque appearance. This design change was due to the thought that imitations of actual aircraft may produce a better result. However, it became readily apparent that this airframe needed either larger wings or bigger motors as, once all the electronics and sensing equipment were put in, there was simply not enough lift generated for take off. To rectify this, the plane was changed to a 4ft wing with a Clark-Y airfoil and a single rear-facing motor on the wing. This was coupled with a smaller Version 3 and 4 body and two booms going out to the tail to reduce weight in the nose and tail.

Wing attachment to the cockpit: There were many ways to attach the cockpit to the wings. However, being able to take the body of the wings for transportation or storage was found to be an issue that was hard to find a simple solution to. One idea was to utilize 3D printing that would clamp around the winds and attach to the body, yet this would obviously require the user to have access to a 3D printer. Instead, a simple but effective zip tie method was used to securely attach the wings and body. This made it both easy to take apart for transport and storage and very durable in the case of a crash.

4.2 Composition of Aircraft & Cost Analysis

One of the objectives of this project was to create an affordable airframe. The body of the aircraft was primarily constructed of corrugated plastic and was purchased from Home Depot for ($24). Packing tape ($7), epoxy ($5), and hot glue + glue gun ($16) were used as adhesives to keep the body together. The body totaled ($52). In terms of the wing, the primary construction material used was blue extruded polystyrene ($13) purchased from Home Depot as well. Epoxy and packing tape used to construct the body were also used to adhere the wing together. In order to attach the tail to the wings, two 3 mm (⅛ in) aluminum bar stocks were used ($5). Altogether the materials for the wing cost ($18). That said, both the wing and body costs coupled with the additional miscellaneous items purchased amounted to (~$80) for the airframe materials.

4.3 Field Sampling

During field testing, the biggest concern was dealing with take-off/ landing constraints and atmospheric conditions. One of the disadvantages of a fixed-wing aircraft had to do with the amount of available space needed to take off and land. Inadequate space or obstructed airspace can cause crashes, and radio communication errors. One of the issues faced while sampling on Oahu dealt with finding a place where there was enough space for taking off and landing and being in unrestricted airspace. Due to Oahu's military presence and numerous airfields, this became somewhat of an ordeal where scouting for an area became more intensive than originally planned. When looking for an ideal field sampling site, one may want to look at the following factors: (1) open land, (2) calm weather conditions, and (3) minimal foot traffic. Finding a large open area allows for more space and time to adjust a takeoff or landing when needed, as most accidents happen when the aircraft is departing or arriving back onto the runway. An ideal field location will also have generally calm winds, which subsequently create smoother flight conditions. Minimal foot traffic is also an important factor as bystanders can unknowingly become collateral damage in the event of an accident. Hence, conducting the sampling was deliberately done on Friday mornings due to the factors mentioned above. The large field next to the ocean made for a wide-open runway while the morning time meant that winds were generally calm. There was also minimal foot traffic due to the time of day and relatively remote location of Kulaloa.

Figure 20: Location of field sampling site

4.4 Super Adiabatic Conditions

Looking at the previous lapse rates, we see that each figure displays super adiabatic conditions. Super adiabatic conditions come about when a particle of air is cooled at over 9.8℃/km leading to air that is highly unstable. Unstable air can lead to rapidly changing weather as particles of air are rapidly lifted. Going into the sampling phase of this project it was initially thought that the air would be near the dry adiabatic lapse rate, as it was believed that the land (at around 7:30-8:00 am) would not be warmed up enough for there to be a drastic change in temperature. However, contrary to initial belief, it was found that the land was radiating more of its heat quickly rather than holding onto it, leading to a high rate of change in temperature from 0 meters to 120m (400ft) AGL.

Chapter 5

CONCLUSIONS

5.1 Final Remarks on Overall Project Goal

To reiterate, the goal of this project was to produce a low-cost, fixed-wing aircraft that is able to reach speeds of at least 30 km/h, be aloft for at least 15 minutes, and use its onboard sensor suite to log atmospheric base parameters. At a cost of (~$80) for the airframe, an individual can easily make extra airframes in case of a mishap or to have a fleet. Similar off-the-shelf aircraft cost in the range of $160 for a Skywalker 1720 to $1500 for a Swan K1 Pro. These airframes can be made into research aircraft and are very capable. However, they are specifically built for first person view (FPV) flight which means they lack sufficient room inside for a range of sensors. The lighter Mk V wing mounted to the Version 5 body also allowed for longer flight time with one flight being recorded at 19 minutes and 25 seconds. Lastly, unfortunately, the two pitot tubes that were placed on the aircraft to record airspeed were faulty leading to erratic top speeds that could not be trusted. In conclusion, the Version 5 body on the Mark V wing was able to complete three of the four goals set for it satisfactorily.

5.2 Aircraft Performance

Although aircraft performance is a subjective topic, it is important to note how an aircraft performs in certain weather conditions. In ideal, no-wind conditions the version 5 body with the Mark V wing is very stable roll-wise, as its large wingspan does not allow for rapid roll rates. This is demonstrated by contrasting how the Mark V wing performs with the 6 foot long Mark VI wing. Due to the aircraft's relatively short 3 foot (0.9 m) length from nose to tail, the aircraft is sensitive to the pitch axis. This sensitivity is very apparent when compared to the aircraft with the Mk6 wing where roll rates decreased significantly. A setting in the controller called exponential rates is used to reduce the sensitivity of this axis leading to smoother flight. During moderately windy days (5-8 knot winds), the aircraft is buffeted by winds, especially when flying through crosswinds. This is unavoidable due to the design and weight of the aircraft, as the larger cross-sectional area of the body acts as a sail. While heavier payloads allow the aircraft to pierce through the wind better, it does decrease range. Furthermore, at winds above 12 knots, it is not recommended to fly the fixed-wing aircraft as any strong gust will cause the plane to be uncontrollable.

5.3 Further iterations

Future improvements to the aircraft could include easily removable wings. At the moment, zip ties hold down the wing which is simple and robust in a crash but wasteful in the event that the wing would need to come off. Changing the location of the camera module would also be a great future improvement, as the current location for the camera obstructs the left side of the image. A possible location for the camera module would be in the nose, where the battery is currently located. Experimentation with a larger motor and propeller setup may also be informative. Currently, a 1100kv motor with a 10x6 propeller creates anywhere from 520g- 565g of thrust. A larger motor and propeller setup would obviously provide more thrust. However, that said, it would be interesting to see what kind of flight times are achievable on such a setup.

5.4 Future Research

With Dr. Alison Nugent's research group, future research may include using this platform to collect sea salt aerosol. The reason that this aircraft would be used for this research is due to the impact velocity needed to collect a smaller range of sea salt aerosol. Other research that this aircraft would be ideal for would be UAS sounding, especially horizontal sounding, as the UAS is not allowed above 400 feet AGL. Hence, horizontal sounding of areas especially over the transition from land to the ocean would be of interest. Another area that would be a good fit for this application would be UAS coastal surveying whereby the aircraft can fly the same path over many months looking for differences in the terrain. This is especially important in Hawai'i where the loss of coastal properties is an ever-growing issue.

References

Aircraft principal axes. (2022, February 9). Wikipedia. https://en.wikipedia.org/wiki/Aircraft_principal_axes#/media/File:Yaw_Axis_Corrected.svg

All about Aviation. (2020, October 3). *Aircraft Control Surfaces Explained |Ailerons, elevator, and rudder*. YouTube. https://www.youtube.com/watch?v=ehxxvAuXaDQ&ab_ channel=AllaboutAviation

Bob Report Staff. (2011, June 1). *Best of the Best 2011: Personal Aircraft: Twin Engine: Beechcraft King Air*. Robb Report. https://robbreport.com/motors/aviation/best-of-the-best-2011-personal-aircraft-twin-engine-beechcraft-king-air-227115/

DJI Mini 2. (2022). Apple. https://www.apple.com/shop/product/HPFW2VC/A/dji-mini-2-fly-more-combo

DJI Phantom 4 Pro V2.0. (2021). Amazon. https://www.amazon.com/DJI-Phantom-Pro-V2-0-White/dp/B07CXX39Y7

HeeWing T1 Ranger. (2022). RaceDayQuads. https://www.racedayquads.com/products/heewing-pnp-t1-ranger-wing-choose-color?currency=USD&variant=39753597386865&gclid=Cj0KCQjw8O-VBhCpARIsACMvVLMKgP-OQLG3EeI_xUImPdq77LOYQOeVl5XM2517jyPuBsYjDYL5A7saAue1EALw_wcB

Jiang, H., Ren, Y., Jin, Q., Zhu, G., & Liu, Z. (2020). Flexural performances of fiber face-sheets/corrugated core sandwich composite structures reinforced by horizontal stiffeners. *International Journal of Mechanical Sciences*, *168*, 105307. https://doi.org/10.1016/j.ijmecsci.2019.105307

Marchman III, J. F., & Werme, T. D. (1987). Clark-Y Airfoil Performance at Low Reynolds Numbers. *American Institute of Aeronautics and Astronautics*, *2*.

Nugent, A., DeCou, D., Russell, S., & Karamperidou, C. (2019). *Atmospheric Processes and Phenomenon* (p. Chapter 5: Atmospheric Stability). Outreach College University of Hawaii at Manoa.

Parrot Bebop 2 Drone. (2022). Media-Amazon.com. https://m.media-amazon.com/images/I/71b1YNfJtlL._AC_SL1500_.jpg

Shepherd, S. (2015, November 6). *$5 Trainer Build Techniques*. YouTube. https://www.youtube.com/watch?v=aV5hILJe20U&ab_channel=SammSheperd

Skywalker 1680. (2017, January 20). Alicdn.com. https://sc04.alicdn.com/kf/HTB13pGOXUrrK1RkSne1q6ArVVXah.jpg

Swan K1 Pro. (2022, June 15). Shopify.com. https://cdn.shopify.com/s/files/1/0236/4759/products/SwanK1pro_2048x.jpg?v=1636849207

Yuneec typhoon H. (2022). Wikimedia.org. https://upload.wikimedia.org/wikipedia/commons/1/16/Yuneec_Typhoon_H.jpg

ZOHD Talon GT Rebel 1000mm Wingspan V-Tail. (2020). www.getfpv.com. https://www.getfpv.com/zohd-talon-gt-rebel-1000mm-wingspan-v-tail-bepp-fpv-aircraft-pnp.html?gclid=CjwKCAjw7vuUBhBUEiwAEdu2pFuTg7NAuvJFO_8KhDOwZVvrJ6en8Kat4ZUtYKANYtC04UQmTi4SbhoCur0QAvD_BwE