The Variable Sweep Flying Wing:

Investigating a Novel Concept for Small Scale UAVs

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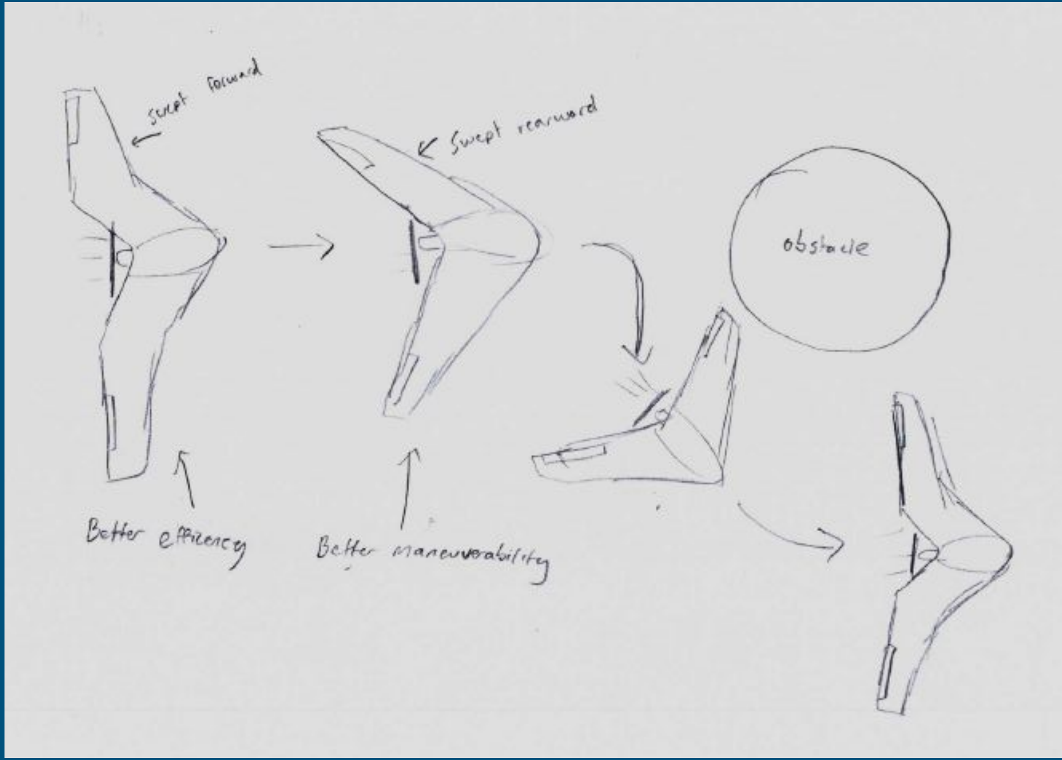
Abstract

The flying wing's simplicity, small form factor, and similar efficiency to conventional configurations are sought-after features when designing unmanned aerial vehicles. What's different about flying wings is that its maneuverability and efficiency are inversely dependent on the sweep angle and center of gravity of the flying wing. A wing with a high angle of sweep, resulting in a forward center of gravity will yield a highly maneuverable and stable, though inefficient aircraft, and vice versa. During different phases of flight, such as the difference between maneuvers and cruise, different amounts of sweep would be optimal. A design which could vary its sweep, thus aspect ratio, center of gravity, and trim, in flight, would be ideal. This project aimed to verify this concept by comparing the variable sweep flying wing with a sweep-optimized but fixed sweep flying wing. This was done by designing and flying a model of both the variable sweep design and fixed sweep design. A self designed flight computer was used to take signals from a remote control and determine how to actuate the various mechanisms on the flying wings. To determine maneuverability, a simple loop was timed to determine pitch rate, pitch being the axis which is affected by sweep. To determine efficiency, the declining battery voltage was used to measure power consumption in flight. Though the variable sweep design didn't outperform the fixed sweep design due to excess weight, this project was able to confirm the concept of varying wing sweep to increase efficiency was true.

Purpose

- Like any design problem, there is no one solution fits all.
- In most cases, conventional designs or fixed sweep configurations would be all that is needed.
- If it is difficult to improve other portions of the aircraft, the Variable Sweep Flying Wing could be an option to better maximise efficiency without sacrificing maneuverability.



Conceptual Sketch

Motivation and Inspiration

- The inspiration for this project came when I was researching the flying wing design.
- As a hobby, I enjoy designing and flying RC planes, which naturally led me to experiment with different designs. As I explored these designs, I became interested in the tradeoff between efficiency and maneuverability based on wing sweep.
- Thus, left my original intent for a model airplane and decided to design a research project out of a flying wing that could adjust its sweep (and thus aspect ratio and center of gravity) to exchange the aircraft's efficiency and maneuverability.

Project Goals

The broad goal of this project was to test the viability of a variable sweep flying wing (VSFW) with the goal to outperform an already optimized fixed sweep flying wing (FSFW) in efficiency while retaining its maneuverability. This involved creating and comparing an optimized flying wing with a modified version of that flying wing which varies its sweep.

This required meeting plenty of smaller goals, such as:

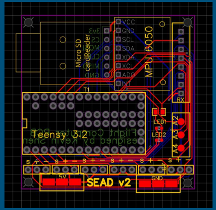
1. Optimizing a flying wing
2. Designing and assembling a flying wing
3. Developing software to transition into different phases of flight
4. Interfacing pilot and automated commands to actuators
5. Accurately comparing aircraft qualities.

Testing Procedures

- To test the viability of a Variable Sweep Flying Wing (VSFW), it needs to be compared with a Fixed Sweep Flying Wing (FSFW).
- The ends result is efficiency, but there also needs to be a test to make that the VSFW can maneuver similarly to the FSFW.
- To test maneuverability, a loop (defined by a positive 360 degree rotation about the pitch axis) would be conducted, and a camera would record the time to figure out pitch rate. Pitch rate is most important since it is the tradeoff with its efficiency.
- To test efficiency, the voltage difference in the battery is measured. The voltage on a Lithium Polymer battery is proportional to the energy remaining.

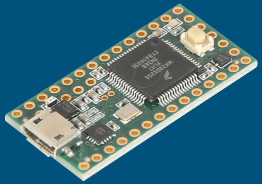
Electronics

Newer, cheaper, and more reliable electronics allowed for the creation of this project. Listed here are the exact electronics (and corresponding parts) used. Everything is a commercial product, except for the Printed Circuit Board which was custom designed.



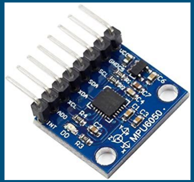
Custom Flight Computer PCB

The Flight Computer is a custom PCB which connects the Teensy with sensors, actuators, and is the "nervous system" of the aircraft. This was designed on EasyEDA.



PJRC Teensy 3.2 Microcontroller

The Teensy 3.2, running at 72 MHz, running 4.5 times faster than a standard Arduino Uno. It is programmed with C++ through the Arduino IDE.



MPU 6050 6 axis Gyroscope and Accelerometer

The MPU6050, also known as the GY-521 measures rotational rate and acceleration in all 3 axis which can be used to estimate the attitude of the vehicle

Toy Quadcopter Motor

The motor of a toy quadcopter can be repurposed to measure airspeed by using the motor and propeller as a generator, which provides a range of voltage which the Teensy can read.

EMAX 1806 2280kv Brushless Motor (with a 6030 propeller)

The Motor and propeller create the thrust which propels the airplane forward. The propeller is a 6030 propeller, meaning that it is 6 inches in diameter.

Flite Test ES9051 Digital Servo

Servos actuate control surfaces and the wing sweep mechanism.

EMAX BLHeli Series 12A ESC

The ESC, or Electronic Speed Controller, takes PWM signals from the Teensy and pulses the power from the battery to the brushless motor to control its speed. Included is also a BEC, (battery eliminator circuit) which provides 5v from the 7.4 volt LiPo battery to the rest of the airplane.

Spektrum 4ch Sport Receiver

The Receiver takes the 2.4 GHz signal from the transmitter (controller) and feeds out PWM (Pulse Width Modulated) signals to the Teensy to process.

Tattu 650 mah 2s Lipo Battery

The Lithium Polymer (LiPo) battery provides an average of 7.4 volts into the ESC to power the aircraft.

Aircraft Sizing

Sizing is a critical component of any aircraft. For this project, is only serves the purpose of getting a flyable UAV. Since I already have a set of standard RC electronics, and the data to go with them, aircraft sizing was based off that. The process began with the Thrust to Weight (T/W) ratio, to get the desired performance. Then, with the takeoff weight the wing surface to weight ratio, or (S/W) ratio is used to calculate the cross sectional area of the wing. Normally, this process would be iterated until exact performance is attained, though for this investigation traditional values for RC model airplanes produced sufficient results.

Thrust of 0.375 kg Desired T/W of 1.5

0.375kg/x=1.5

x=0.25kg *Weight approx 0.25kg*

Desired W/S of 1.9

0.25kg/x=1.9

x=0.13m^2 *0.13 meters squared wing surface area.*

Wing Sweep Optimization

Wing sweep optimization is a vital part of this project, as once the optimal sweep is found the VSFW won't attain any extra efficiency from simply a more efficient sweep angle, (which would invalidate the tests).

I wrote a computer program in MATLAB which tests all realistic sweep angles and calculates the drag, in the end outputting the most efficient configuration.

```

%modifiable variables

A=0.129; %Wing area
rch = 0.188; %root chord
tch = 0.07; %tip chord
StabSetAsPercOfMAC=0.15;  %Percent of MAC for CG location
wa=0.25; %flying weight
AirfoilTorque=0; %positive is pitch up, zero for a symmetrical airfoil
sp=0.7; %Structural span.

%iteration code

a=0; %sweep interation start
b=0.1; %sweep iteration interval
c=40; %sweep iteration end
sdegV=[a:b:c]; %sweep iteration vector
d=(c-a)/0.1; %number of iterations


Cdip=100000; %starting drag value (arbitrary number)
for i=1:d
PrevCdip=Cdip; %Variable to compare iterations
sdeg = sdegV(1,i); %sweep for this combination

HorizSp=cosd(sdeg)*sp; %Aerodynamic span
Ar=(HorizSp^2)/A; %Aspect Ratio

TaperRatio=tch/rch; %taper ratio
MAClength= (rch+tch)/2; %length of the Mean Aerodynamic Chord (MAC)
MACdist=(sp/6)*((1+2*TaperRatio)/(1+TaperRatio)); %Distance from middle of flying wing to MAC
AC=MAClength/4; %MAC distance (from leading edge)

%Calculate the force needed to trim the airplane, and add it to the weight
ACDistFromTP=tand(sdeg)*MACdist+AC;
CGDistFromTP=tand(sdeg)*MACdist+(StabSetAsPercOfMAC)*MAClength;
CGtAC=abs(ACDistFromTP-CGDistFromTP);
ACtWT=(tand(sdeg)*(HorizSp-MACdist)-AC)+tch;
TrimForce=(((wa*9.81*CGtAC)/ACtWT)-AirfoilTorque);
we=wa+TrimForce;

e=1.78*(1-0.045*Ar.^0.68)-0.64;  %Oswald Span Efficency

%Calculate Wing Drag (take in account parsite drag of wing, induced drag,
%fuselage drag (determined through CFD estimates), and trim drag
v=10; %Velocity at 10m/s cruising speed
p=1.225; %Air pressure at sea level
q=(1/2)*p*v^2; %dynamic pressure
L=we*9.81; %Calculate lift force
Cl=L/(q*A);  %Coefficent of lift
Cdi=(Cl^2)/(pi*Ar*e);  %Induced drag coefficent

Cdp=0.023*q*A;  %Parasite drag coefficent

Cdip=(Cdi+Cdp); %Wing coefficent of drag

%iteration comparison
if Cdip < PrevCdip
    bestDrg=Cdip;
    Sweep=sdeg;
    Span=HorizSp;
else
end
end
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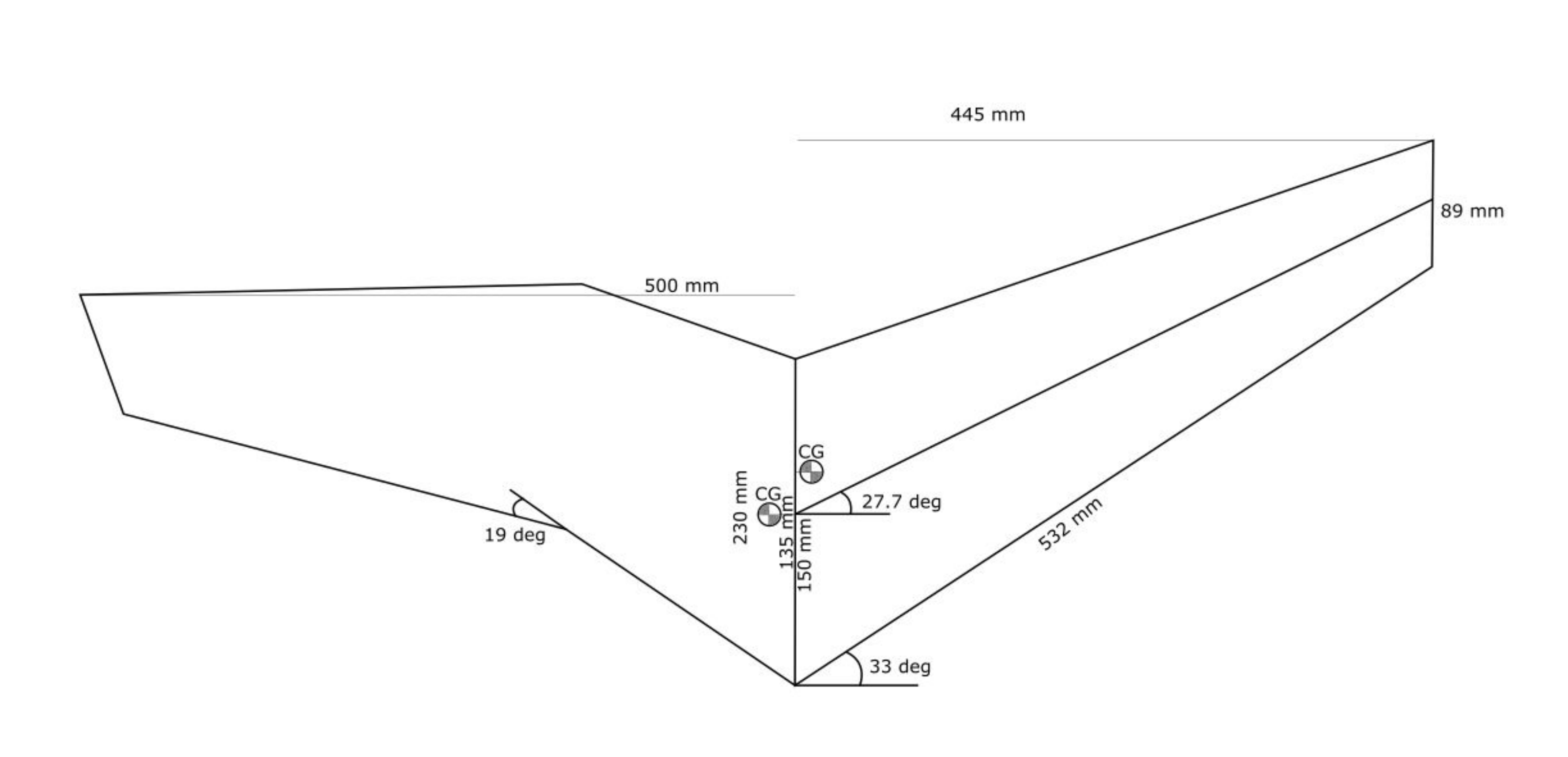
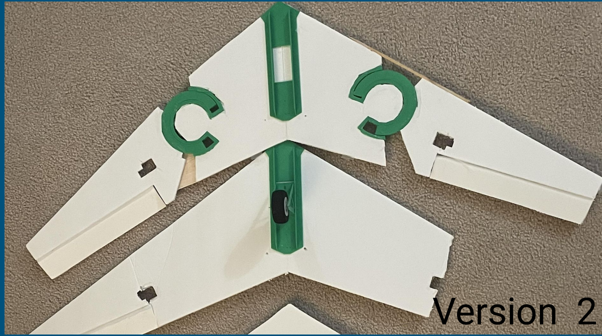


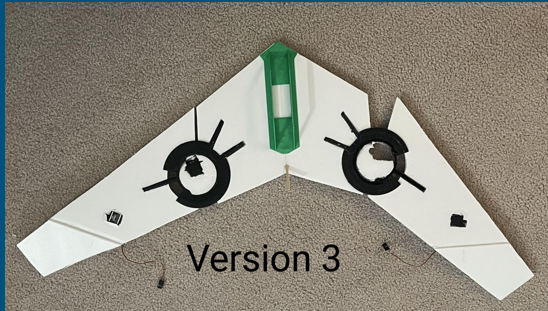
Optimized Aircraft Dimensions

Prototype Versions

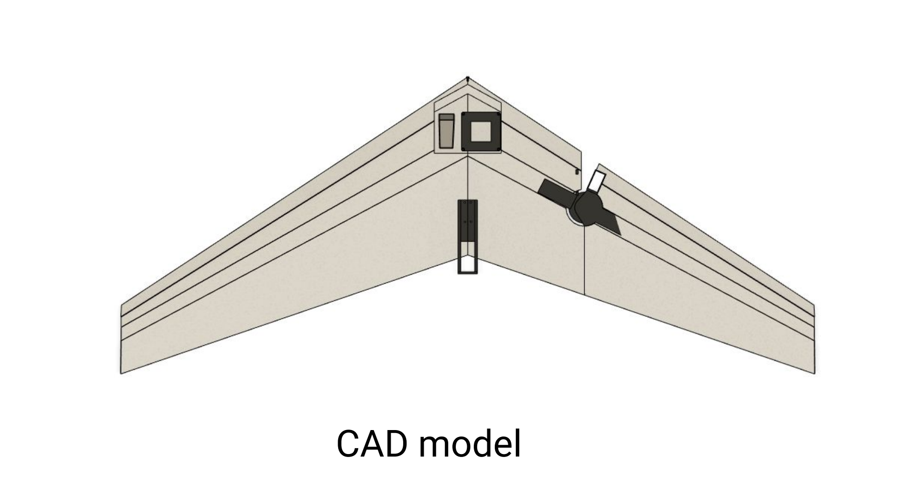
Three versions of the VSFW and FSFW would be tested before the final version.

- Wing sweep mechanism: Version 1 used complaint, or bendable joints for simplicity. While this worked, the slight bendiness in other directions caused an unstable wing, making it impossible to fly. The next versions used rigid joints.
- Airfoil selection: A traditional airfoil is more aerodynamic, but a flat or stepped airfoil would be simpler. Version 1 used a traditional airfoil and version 2 and 3 used stepped airfoils. In the end a traditional airfoil was used for more stable flight.





Final Design



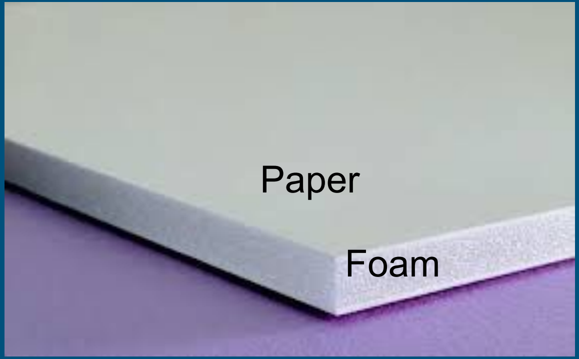
Materials, Construction

Materials:

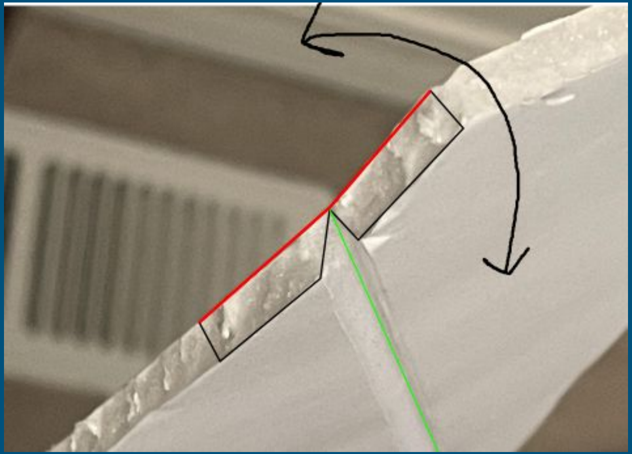
- Foamboard, a paper foam sandwich material which is lightweight and cheap, and forms most of the aircraft, including hinges and control surfaces.
- Polylactic Acid (PLA) plastic formed by a 3D printer was used for more intricate parts, like mounting electronics.

Construction:

- CAD Model was flattened out into a 2D shape, which could be cut from foamboard using a utility knife.
- Servos, mounts, and foam were glued together using hobby hot glue, which was easy to work with and filled in imperfections.

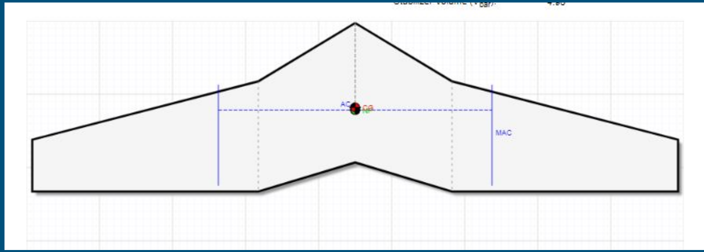


Above: Foam Board Cross Section
Below: Control surface joint made from foam board. Red is the connected paper, Black is the cross section of the foam, and green is the hinge.



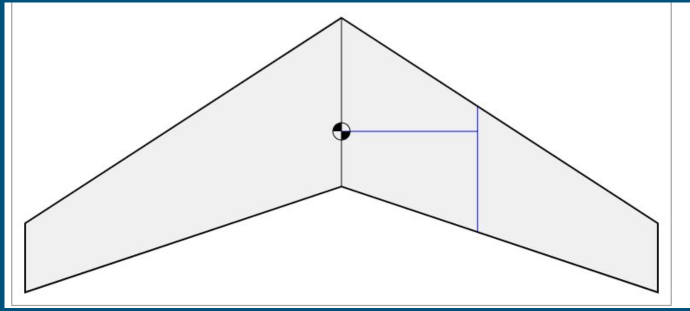
Center of Gravity

- Center of gravity (CG) relative to center of pressure (CP) affects the stability of the UAV.
- A forwards CG compared to CP will be more stable but create more drag from trim.
- The FSFW has its CG at 15% of the Mean Aerodynamic Chord (MAC), which is standard for experimental flying wings.



VSFW in forward position

- The VSFW in its swept or back position has the same center of gravity location as the FSFW, as its shape is the same.
- When the wing sweeps forward the center of pressure will also move forwards and thus the center of gravity will move backward of the MAC, aligning with the Neutral Point at 25% of the MAC.
- This will require much less trim, but with such a short distance between the center of gravity and the control surface it will be much less maneuverable and stable.



VSFW in rearward position, and FSFW.

Programming

Basic Information

- Code was written in the Arduino Internal Development Environment (IDE), which uses C++.
- Two versions of code, one for the VSFW and one for the FSFW. The only difference is that the FSFW has no sweep change and trim adjustment.

Code control logic:

- Read input from pilot
- Read sensor (gyro, accelerometer, airspeed)
- Determine correct flight mode
- If manual flight requested, map controller signal onto elevons and output. Set wing sweep rearward and add trim.
- If cruising flight requested, map controller signal onto elevons and output. Set wing sweep forward and remove trim.
- If loop requested, set throttle to full and elevons to full deflection.

Code structure:

Sketch Description

Library Declaration

Variable Declaration

Void Setup

Void Loop

Mode Decision

Mode 1: Manual flight

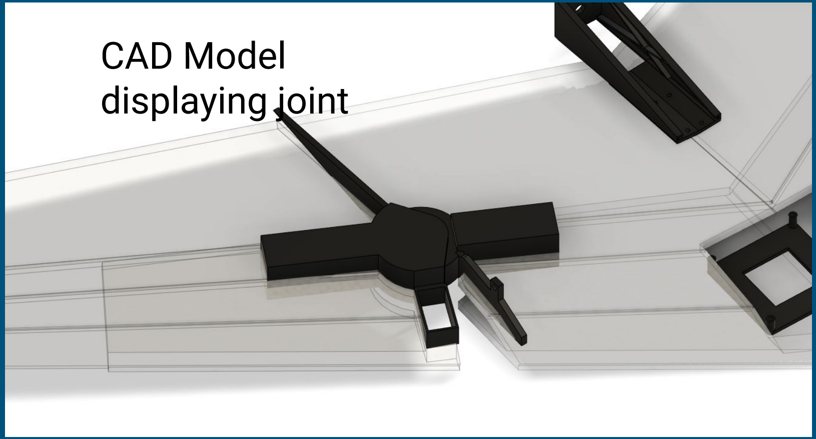
Mode 2: Cruising flight

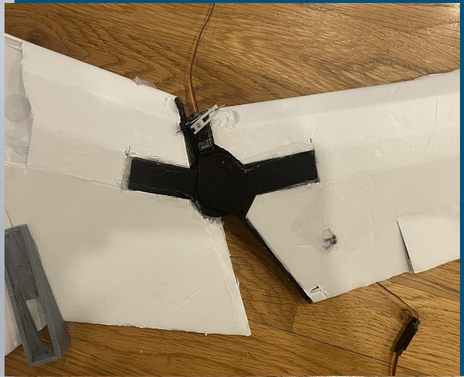
Mode 3: Do a loop

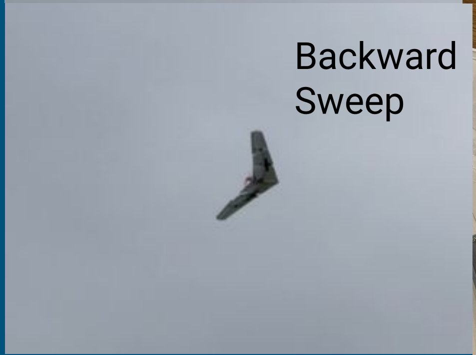
Functions

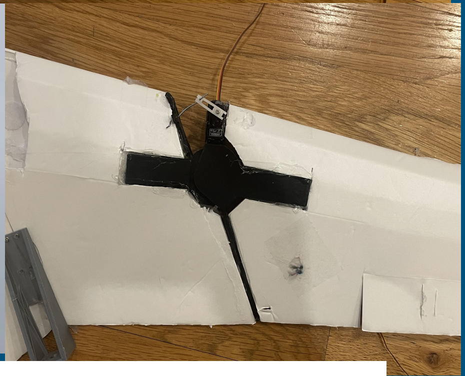
Wing Sweep Mechanism

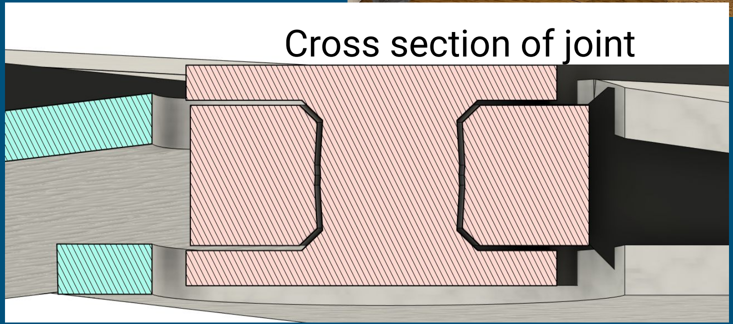
The Wing Sweep mechanism was 3D printed in a single part. It is a simple through hole hinge, with spars extending out of both sides to be glued to the foam. It also holds the servo and as well, and added approximately 54 grams to the total weight.











Aircraft Safety

UAVs can be dangerous, though safety measures were taken to ensure that nobody got hurt.

- FSFW is 218 grams, and VSFW is 272 grams
- Both aircraft are categorized as “Small UAVs”
- Built from MakerFoam Foam Board, which is soft.
- Assembled with hobby Hot Glue.
- 6 inch propeller at the rear of the aircraft.
- Throttle Cut Off during emergencies.
- 7.4 volts of current maximum inside the aircraft.
- Airspeed kept below 20 m/s.
- 1m wingspan.
- Flown at a local park, with no people around.

Raw Efficiency Data

Flight No.	Date/Time	Flight Time	Battery Start	Battery End	Difference	Voltage change per minute
FSFW	3/5/21, 3:42	6 min	8.39 V	7.65V	0.74V,	0.12V/Min
VSFW	3/8/21, 2:16	2 min, 40 sec	8.33 V, 97%	7.9 V	0.37 V	0.14V/Min

VSFW	Total Time	Deg/Sec
1	4	90
2	5	72
	Avg. Deg/Sec:	81

Raw Maneuverability Data, Variable Sweep Flying Wing

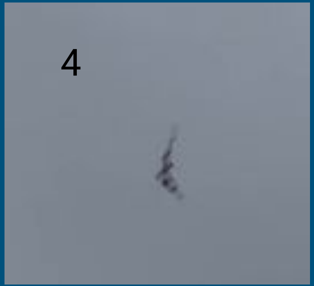
Raw Maneuverability Data, Fixed Sweep Flying Wing

FSFW	Total Time	Deg/Sec
1	4	90
2	4.5	80
3	3	120
4	3.5	102.8571429
5	3.5	102.8571429
6	4	90
7	3.5	102.8571429
8	3	120
9	3	120
10	4.5	80
11	3.5	102.8571429
12	4	90
	Avg. Deg/Sec:	100.1190476

UAV in flight

Maneuverability Test

- Sample size very small and uneven, resulting in difficult conclusions.
- As far as an average, the VSFW doesn't seem to do quite as well as the FSFW.
- Based on the data, but also qualitative observations while piloting, its safe to say both can definitely maneuver well. This is important because it shows that the tradeoff is made: while the wing is in its forward sweep configuration, it is unable to even complete a loop at all.
- It's likely that the VSFW does perform slightly poorer because of the higher takeoff weight to wing area ratio.



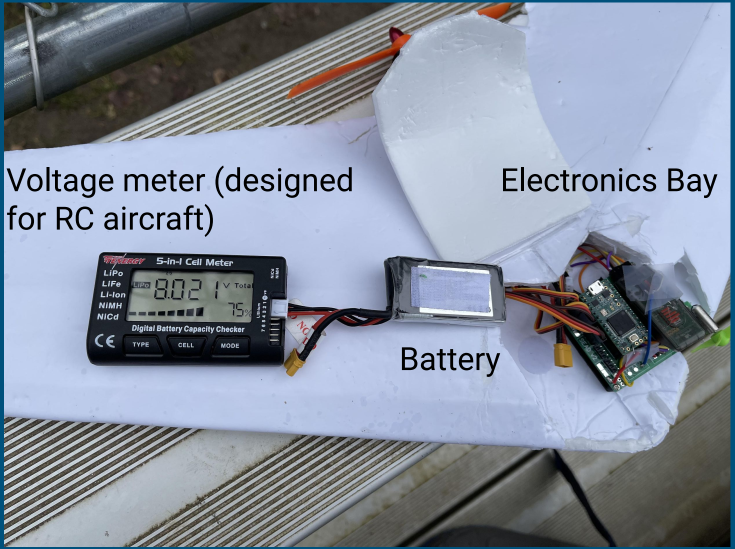
Loop End

Loop Start

Efficiency Test Results

- No efficiency advantage over the FSFW yet, even a slightly poorer performance.
- Still, it is important to note that the VSFW had a 25% higher takeoff weight, and was only 17% less efficient. Though it isn’t a perfectly linear relationship, based on the data, lowering the sweep angle to decrease drag has been shown to be true.
- Poorer overall performance was likely due to large amounts of excess weight, not only from the wing sweep mechanism but also repairs from the many crashes.

Battery Voltage Check



Sources of Error

- These tests have quite a few possible sources of error which may disrupt the data. The efficiency and maneuverability tests were not perfect by any means, especially as I, the pilot, am a human variable in this equation. Being inexperienced in flying these aircraft, irregularities in flight speed, how tight of a pattern was flown, and the smoothness of the flight depending on my skill that day could all drastically change the end result.
- This is made much more apparent as there was only one flight for the VSFW. Though it can be argued that the small irregularities of a flight will balance each other out, a single flight is still essentially a sample size of one.
- As far as the maneuverability aspect, a multitude of sources of error can come here. Since the position of the UAV inconsistent, and the start and stop times for the loop are simply estimated by looking at the footage, the exact timing of the loop is hard to measure well. Theoretically this would balance itself out over enough data points, but the VSFW only had 2 points of data.
- Finally, smaller impacts such as manufacturing defects, weather, servo trim, and temperature can play a role on performance.
- All this added together means that very little real and usable data can be extracted from this experiment, apart from a general idea of if the idea is truly useful or not.

Is this Viable in the Real World?

- The concept that changing the sweep of a flying wing to trade between maneuverability and efficiency can work, but will require better design than what was accomplished in this research project to beat an already optimized UAV.
- For the applications the VSFW is intending to solve, implementing another solution such as thrust vector control could also accomplish the goal of increasing maneuverability while retaining a wing which is more efficient.
- It’s important to not get to conclusions too quickly, because this research project is nowhere near a completed stat. The next step to exploring the concept would be to continue testing with a better and more accurately built UAV. An early test with roughly assembled foamboard and hot glue works well for an initial test, but does not yield accurate results.

Software Used

Autodesk Fusion 360- Computer Aided Design

EasyEDA- PCB design

Arduino IDE: Used for flight computer programming

MATLAB: Used for sweep optimization program

Ultimaker Cura- 3D printer slicer software

Inkscape- Used to create foam printouts

Autodesk Flow Design- Approximate drag for certain components (for the sweep optimization program)

Wondershare Filmora- Video Editing Software used to analyze footage & determine maneuver time