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Giddy Guidance: Low-cost 3D aircraft with integrated autopilot and stabilization

Mark Lohatepanont , '24

ENGR 90: Giddy Guidance

Low-cost 3D aircraft with integrated autopilot and stabilization

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Contents

Project Specification

My project had two main goals. The first was to design and construct a remote-controlled, fixed-wing, single-engine electric aircraft. The second goal involved developing a control system based on state-machine principles that could generate and execute a pre-planned flight plan. This project resulted in two key products: a proof of concept for a functioning aircraft and a flight controller that mirrors the capabilities of a standard controller and receiver. Overall, the aircraft is designed to be low-cost, 3D printed, and modular, with a particular focus on ease of deployment, recovery, and repairability.

I was motivated to do this based upon previous summer research at Swarthmore College where I used drones to collect data from crop fields and count the number of crops and predict the yield of that field.

In this project I used the open-air wind tunnel to test passive stability of aircraft and computational fluid dynamics (CFD) simulations to generate simulations of the aerodynamic properties of my designs before printing them.

The outcome of my project was that I was successfully able to create a proof-of-concept aircraft which fits the general definition of stable and controllable aircraft. I was also able to produce a basic proportional flight controller based upon an Arduino that replicated the functionality of off-the-shelf flight controllers.

Background Information

Motivation

The motivation to develop drones for remote sensing in agriculture stems from a desire to integrate advanced technology with traditional farming practices to address growing global challenges. As the world's population continues to rise, the demand for food increases correspondingly, necessitating more efficient agricultural methods. Drones, equipped with cutting-edge remote sensing technology, present a unique solution to this need by enabling precise monitoring and management of crop health on a large scale.

During my summer research in Sophomore year and under the advice of Professor Zucker, I researched integrating visual drone imaging technology in agriculture. The ability of drones to gather high-resolution images and data from vast crop fields quickly and with minimal human intervention is important and many fields of remote sensing stem from the ability of drones to do this. My research focuses specifically on predicting crop yields and I was successfully able to determine crop yields to a reasonable accuracy. However, the potential of this technology also extends to help in identifying pest infestations, nutrient deficiencies, and water stress areas. Using remote sensing and by pinpointing these issues early, farmers can take specific, targeted actions to mitigate problems, leading to better crop management and reduced waste of resources.

Finally, I am motivated by the environmental benefits that drone technology can offer. Traditional farming methods often involve extensive use of water, fertilizers, and pesticides, some of which can be detrimental to the surrounding ecosystem. Drones allow for precision agriculture applying resources only where and when they are needed, which significantly reduces the environmental footprint of farming operations. Drones will be used to augment existing precision agricultural methods but help by providing information to farmers faster, more detailed and with larger macro scale accuracy than humans or robots down in the field may not be able to obtain.

Some axillary motivation is that I also want to develop a robust, and cheap solution to building autonomous drones. This can be used in the field where advanced equipment is unobtainable and there is a need for disposable aircraft in dangerous environments. Further, attaching sensors to the aircraft could also be possible and this would make remote sensing easier. Remote sensing is important as it offers greater information about the environment and could help to combat global warming, wildfires, and aid in smart agriculture.

Basic Aerodynamics

To understand the basic elementary principles which I used to design my aircraft a basic understanding of aerodynamic principles must be considered.

Lift Generation

Lift is generated by multiple parts of the aircraft, and the concept of lift only being generated by wings is a fallacy. However, it is true that wings generally have the largest component of lift. Lift is a complex topic but it can be simplified into two main reasons. The first is a pressure difference that occurs as wind travels over a wing. The top of the wing generally has a faster air velocity, and the bottom has a lower velocity because of the curved shape of the wing. This velocity differential generates a low-pressure zone on the top of the wing and a high-pressure zone below the wing. This pressure difference is what causes a force to be exerted in the positive vertical direction. The second reason is that when a wing is slanted upwards, as air hits the wing the force is split into a positive vertical and negative drag component. These two reasons are why lift is generated. The mathematical derivation is complex but gladly there exists a modern lift equation which simplifies these reasonings. This equation is known as the modern lift equation and is shown in Equation 1.

$$\mathrm{L} = \mathrm{C_l} \times \rho \times \frac{\mathrm{v}^2}{2} \times \mathrm{a}$$ *Equation 1 Modern Lift Equation*

Equation 1 specifies that the lift of a wing corresponds to a C_l, the coefficient of lift, which is determined experimentally in wind tunnels and can be obtained on a case-by-case basis for standard airfoils. Rho, ρ is the density of air, typically taken at sea level, v, the velocity of the air passing of the wing, and a, the wingspan multiplied by the wing chord.

Control Surfaces

Control surfaces exist to control the aircraft and are also technically wings. There exist three main control surfaces, the elevator, rudder and ailerons. Each controls a corresponding axis of rotation. The elevator controls pitch, rudder controls yaw, and ailerons control roll. The full complexities of control surfaces is too difficult to explain completely here, but take note that each of these control surfaces are controlled generally by a servo and has a 90 degree angle of rotation.

Stability

Stability is another main concern with aircraft. The general concept of stability comes from both rocketry and aircraft and states that the center of gravity (CG) of an aircraft must always be leading (in front) of the center of pressure (CoP). This can be explained In the following figure 1 which describe two possible cases. Case 1 is where the CoP leads the CG and case 2 is where CG leads the CoP.

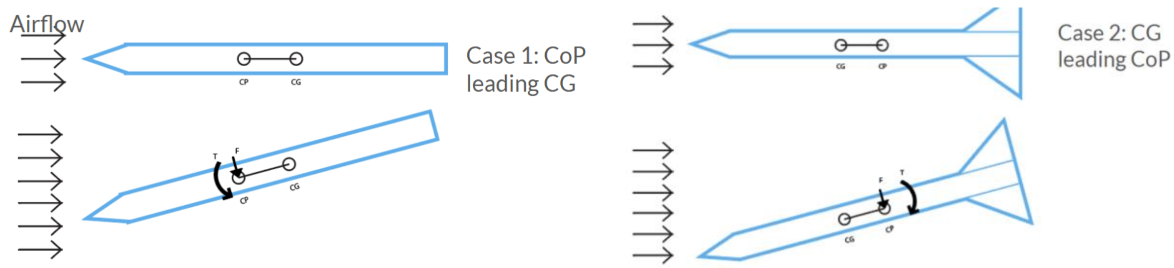


Figure 1 Cases of CG CoP placement

Let's first examine the unsafe case, Case 1, Where the CoP leads the CG. In this case, you can image the CG is a pin which is the core of the aircraft, while CP, is where a force acts. This force is a result of the airflow which is why the CP is where this force is acting from.

In case 1, let's assume a disturbance occurs which causes the aircraft to pitch down. Due to the angle now made by the aircraft, a force is now pushing down on the aircraft. This causes a torque, T, to be generated which forces the aircraft to continuously pitch down with no way to correct itself.

In case 2, let's assume the same disruption occurs. In this case, a torque T is once again generated, but it pushes the part of the aircraft that is rising back down to a stable position. This is what is generally called static stability and is an important concept in flight.

This is always why the CG should lead the CP. This is the only crucial design element that I learned to follow after my first iteration.

Equipment and Software

For this project I wanted to use modern technology like 3D printing to create a system which would allow for easy replacement parts to be printed and for the aircraft to be fixed quickly in the field. This project also aims to lower the cost of creating remote sensing aircraft that can be applied directly by farmers without the need for intermediate companies which lower waste and increase efficiency for individual farmers.

Compared to other solutions, remote sensing aircraft are not new, but they are expensive. Common solutions are produced by companies like Sensefly, which produces the EBee Agriculture[1], which costs

[1] (RMUS, 2024)

approximately $12,000, or the DJI Argus[2] which costs $20,000. These are infeasible for small farmers to obtain, and this restricts their access to higher efficiency agriculture.

Design Requirements and Constraints

Constraints

This project was conducted at Swarthmore College, with strict regulations on aircraft flight and testing. This is driven by internal policy and proximity to Philadelphia international airport. This drives some safety constraints on weight and altitude of aircraft to be tested. This means that the aircraft cannot be over 2kg in weight and cannot fly or be tested at over 300 feet (90 meters).

Further, I am constrained by some of components as I am repurposing a previous project. The brushless motor which I am using with a 4" propeller will provide approximately 4N of thrust, and this constrains the weight and acceleration of the aircraft. Furthermore, based upon the airfoil I used, the Eppler airfoil constrains the maximum lift I will be able to produce. This is discussed in the implementation details where I apply CFD analysis to determine the properties of my aircraft.

Requirements

Driven by my motivation to create a remote sensing platform, the requirements of this project are curated to support this platform. Previous experience suggests that to meet the requirements of operating out of rural environments suggests that the drone should be able to launch and land without a runway. This means a reinforced bed body for landing and ergonomic enough to be able to be launched via a short throw. Further, for the aircraft to be able to sense enough information and collect enough data, the aircraft should be able to fly for roughly 30 minutes and at a stable flight with no significant turbulence. This leads to a more technical definition of stability where the center of gravity of the aircraft should lead the center of pressure of the aircraft and the center of gravity should be approximately one fifth of airfoil's chord down from the leading edge of the airfoil.

Evaluation Methods

I will evaluate each of my requirements and constraints by testing my aircraft in the real world, the open-air wind tunnel at Swarthmore college, and via CFD. Stability will be tested first in the open-air wind tunnel where I will induce some turbulence by disrupting the aircraft in the airflow and waiting to see if it realigns itself with the airflow. m

Professional Standards

Professional, there are many requirements which govern aircraft. The federal aviation administration (FAA) recommends the following Title 14, Code of Federal Regulations (14 CFR), part 21, section 21.191(g) which defines the requirements of amateur built aircraft. This is for human capable aircraft. Drones are subject to less restrictions but are still governed by the FAA[3]. The main requirements are that during the process of my research, my drone weighs less than 55 pounds

[2] (DJI, 2024)
[3] (FAA, 2024)

(24kg), that it not be used for commercial purposes, and I abide by flight restrictions. However, while the FAA does provide these resources, not many of them are standardized and not heavily enforced. The FAA officially is still currently in the process of renewing their standards.

Since Philadelphia airport is also in range of Swarthmore, as previously mentioned, this is a flight restriction and therefore to not breach airspace, to remain below 90m.

Constraint and Requirement Summary

Constraints and requirements checklist dictated in table 1 details constraints and requirements that my project must operate under.

Constraints	**Requirements**
Brushless Motor only contains 4N of thrust	Drone should fly for ~30 minutes
My maximum lift is constrained by wingspan which is subject to change	Needs to be thrown as no landing gear will be designed
Maximum flight ceiling of 90m to comply with flight authorities	Drone should be less than 2kg so that it does not injure someone on impact
Battery capacity is sub 3000mAh	Center of gravity should lead center of pressure for maximum stability
Sub $400 cost	Drone should be stable during flight
	Have a high enough velocity at throw that enough lift is generated by the wings. (Approximately 7 meters per second)

Table 1: Constraints and Requirements table

Implementation Details

Design Elements

The basic design elements of my aircraft consist of four main sections. These sections are the nose, fuselage, tail, and wing, all of which are described below in Table 2: Component List

Component	**Description**
Nose	Nose bay contains electronics, first person viewing equipment, and batteries.
Fuselage	The fuselage joins together the nose, wing and tail components.
Tail	The Tail section contains the rudder and elevator control surfaces bounded together in a V Tail setup.
Wings	A symmetrical set of Tapered Eppler wings with inverse symmetric aileron controls.

Table 2: Component List

Designs Discussed

Through the entire process three aircraft distinct drones were constructed. My original version (Version 0) was designed with no real decision considerations other than balancing lift and weight. Version 1 which improved upon the lift and weight with added center of gravity and pressure considerations and then finally a version 3 which took the two previous versions in account and also balances some of the torque around the aircraft for improved control surface maneuverability.

Original design and early work

My original design took inspiration from V tail setups. I chose to use a V tail as opposed to a more traditional inverted T tail because V tails are known to have lower drag, lighter components and this leads to improved maneuverability (Vatandas, 2015). A general composition of the different types of tails is shown below with the V Tail being shown on the left of Figure 2 V Tail and Inverted T Tail Setup.

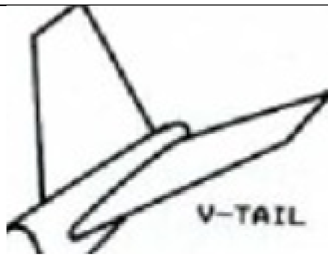
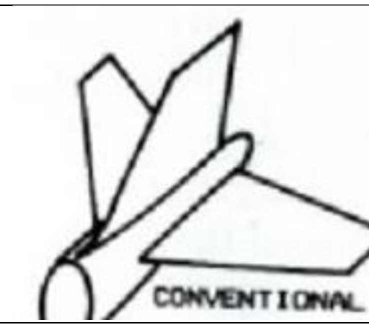
	
V Tail	T Tail

Figure 2 V Tail and Inverted T Tail Setup[4]

My early work wing selection focused on constructing a wing from a NACA 2412 profile with flat, pancake type fuselage. The basic models I created is shown below in Figure 3 Original Design.

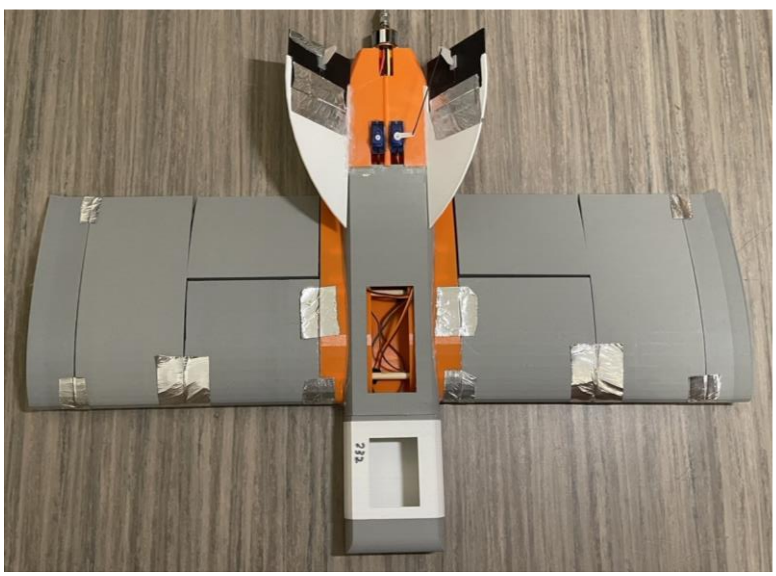


Figure 3 Original Design

This aircraft was focused on a minimalistic design with as few features as possible. However, this also came at the cost of a center of gravity (CG) that was far behind the center of pressure (CoP) of the aircraft. This led to this aircraft not being very controllable. This is because the motor at the rear of the aircraft weighs heavily on the body and the nose, which only contains the battery, is not enough to

[4] (UENGINEERIABLOG, 2015)

compensate for it. The approximate lines for the CG and CoP are shown below overlayed in red (CG) and blue (CoP) lines drawn below in Figure 4.

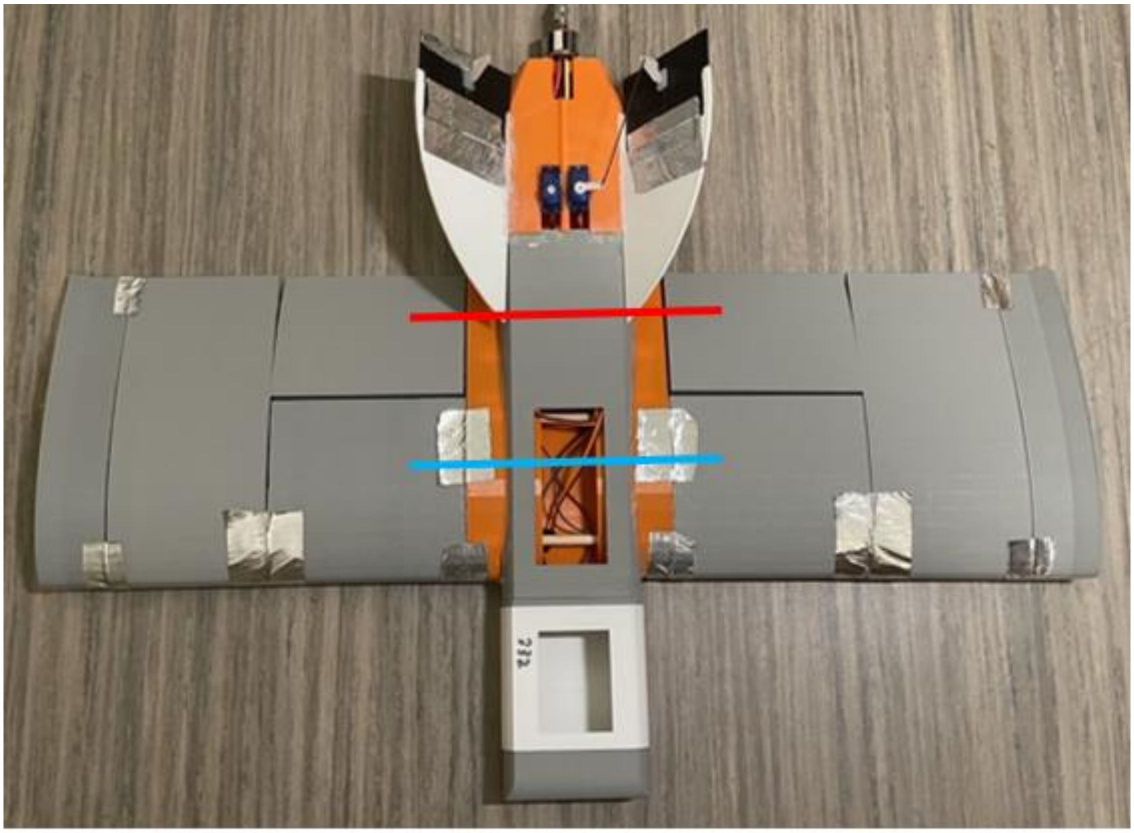


Figure 4 Original Design with CG and CoP

Having the CG behind the CoP leads to any pitching moment on the aircraft being amplified and this means that during launch conditions, the aircraft would pitch up continuously until it stalled in midair. This design led to me modifying my design to have a larger nose and longer nose section which in turn should help pull the CG towards the front of the aircraft. Further, as the mass of my aircraft grows, it becomes more necessary to increase the amount of lift my aircraft makes. This means increasing the size of my wings.

New Design Considerations

After the failure of the first design, I first chose to redesign the wings. Given time constraints and the fact that I wanted to use an already documented wing to help with my calculations I chose to use a new Eppler 205 (E205) wing, which has seen success in many 3D printed aircraft, most recently by the company Flightory. I chose to use the wings designed by Flightory[5] because they provided good documentation on wing performance and my own wings could not be tested easily.

[5] (FLIGHTORY, 2024)

Now deciding on the wing, I can calculate the approximate lift profile of the aircraft. The general lift equation is shown in Eq 1.1. This can be combined with the parameters of the wing that are taken from Flightory and this is shown in Table 3 General Wing Data.

$$L = C_l \cdot \frac{1}{2} \rho \cdot v^2 \cdot s \quad \text{(Eq 1.1 Lift Equation)}$$

Table of Wing Data	
Wingspan	1305mm
Length	830mm
Wing Area	0.275 m^2
Root Chord	240mm
Aspect Ratio	6.3

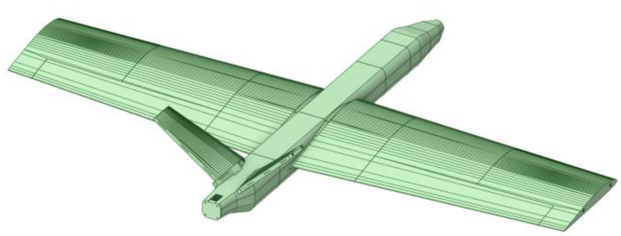
Table 3 General Wing Data

In Eq 1.1, L is the total lift, C_l is the coefficient of lift, ρ is the density of air at sea level, v is the velocity and s is the top surface area of the airfoil. For the purpose of our calculation the coefficient of lift will be approximately 0.6[6], corresponding to an angle of attack of 3 degrees. The density of air will be $1.225kgm^{-}3$ and we will preselect a takeoff velocity of $10ms^{-}1$. The surface area of the wing is taken from the previous table and substituting in this data in Eq 1.2, we obtain an approximate lift of 10N.

$$L = 0.6 \cdot 0.5 \cdot 1.225 \cdot 10^2 \cdot (0.275) = 10N \quad \text{(Eq 1.2 Substituted Lift Equation)}$$

This indicated that at 10 meters per second, with an angle of attack of 3 degrees, the maximum lift being generated by our wings would be 10N, indicating approximately 1 kg of lift. This is approximately equal to the weight of the aircraft.

Knowing the maximum weight drove some design considerations and I eventually focused on a new design. This model, which represented the bulk of my efforts during this project, applies my learnings from the original design. A CAD drawing is shown in Figure 5.



[6] (Airfoil Tools, 2024)

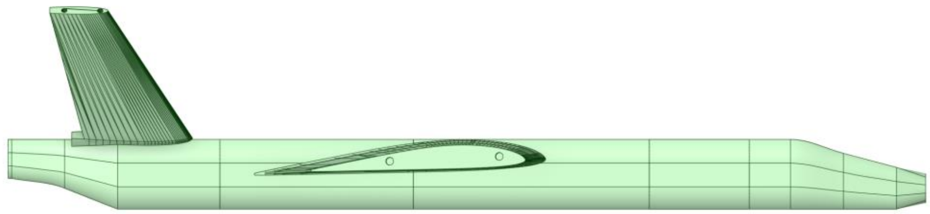


Figure 5 New Aircraft CAD Design, Isometric and Side Profile

This newer model tucks the tail closer to the body and extends the front of the aircraft by approximately 150mm. This should have ideally extended the center of gravity forward, because of the mass in the nose, which contains the battery. The physical product I created is also shown in the following Figure 6. An associated version with annotations is shown in Figure 7 where I annotate the right aileron, elevators, and other large sections. It should be noted that a left aileron exists at the same spot on the left wing.

Figure 6 3D Printed Aircraft

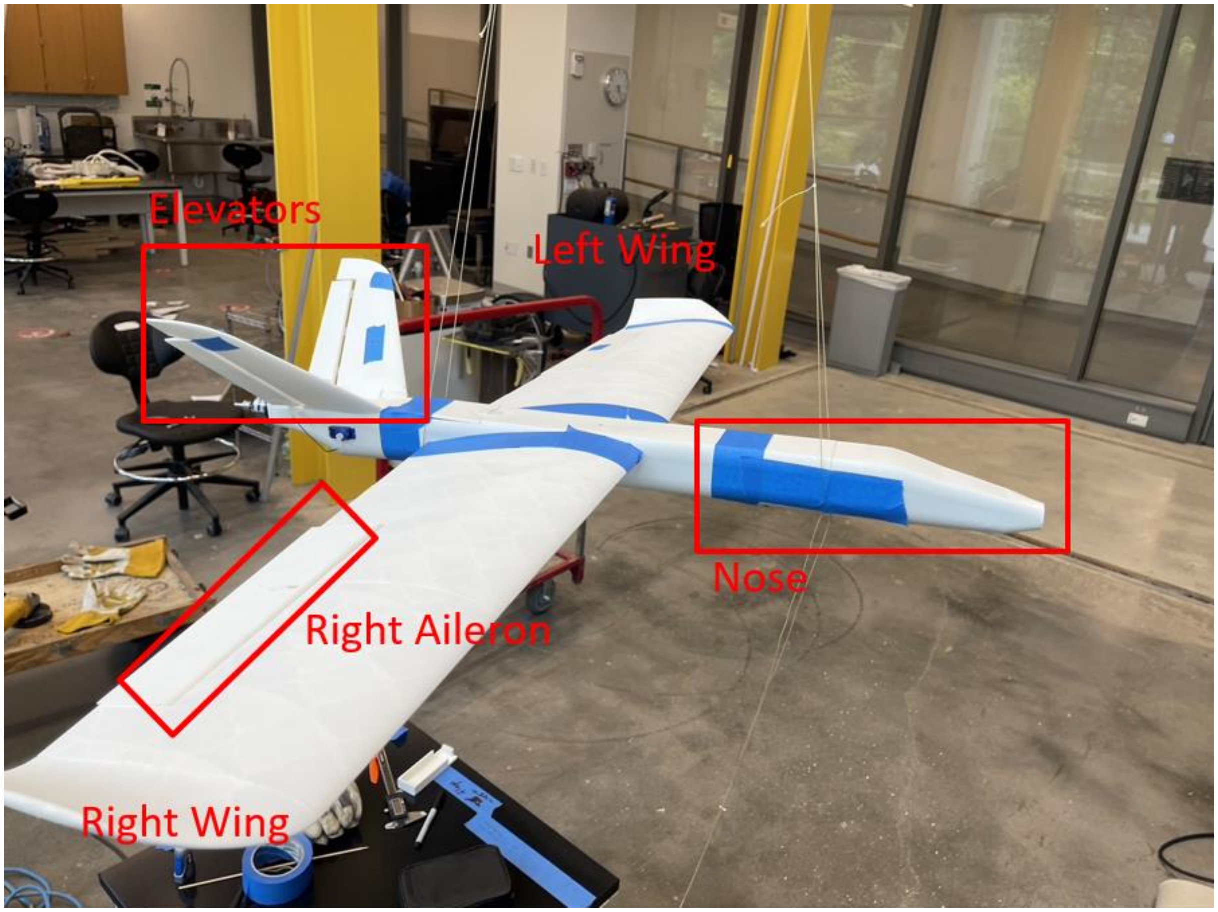


Figure 7 Annotated Aircraft

This aircraft fits the ideal definition for a stable aircraft discussed in the background section, however during initial testing, I had issues with controlling the aircraft using the control surfaces. This was particularly apparent with the pitching moment where the rear elevators were unable to pitch the aircraft up and down. This was determined qualitatively whereby actuating the elevators led to no reasonable change in the stability and movement of the aircraft. This led me to attempt to perform computational fluid dynamic (CFD) simulations and wind tunnel tests in the open wind tunnel to confirm the properties of my aircraft with particular interest in how much force the elevator puts on the nose aircraft.

Experiments

The experimental goal of my work in the wind tunnel was to test the elevator control surfaces and to measure the force placed upon the front and rear of the aircraft. The experimental setup, shown in Figure 8, uses two springs, attached to the front and rear of the aircraft and we expect to use the elevator to be able to see a change in forces in the springs. It is expected that if we force the elevators up, which leads to a pitch down, that the forward spring extends (indicating a higher force being placed upon it) and the rear spring contracts (indicating a less force being placed upon it). The opposite also should occur with pitching the aircraft up should lead to a shorter extension on the forward spring, and a higher extension on the rear spring. The independent variable in this experiment is the angle the elevator makes, and the dependent variable is the extension on the springs. This experiment will be conduct in a near uniform airflow with approximately a speed of 5 m/s.

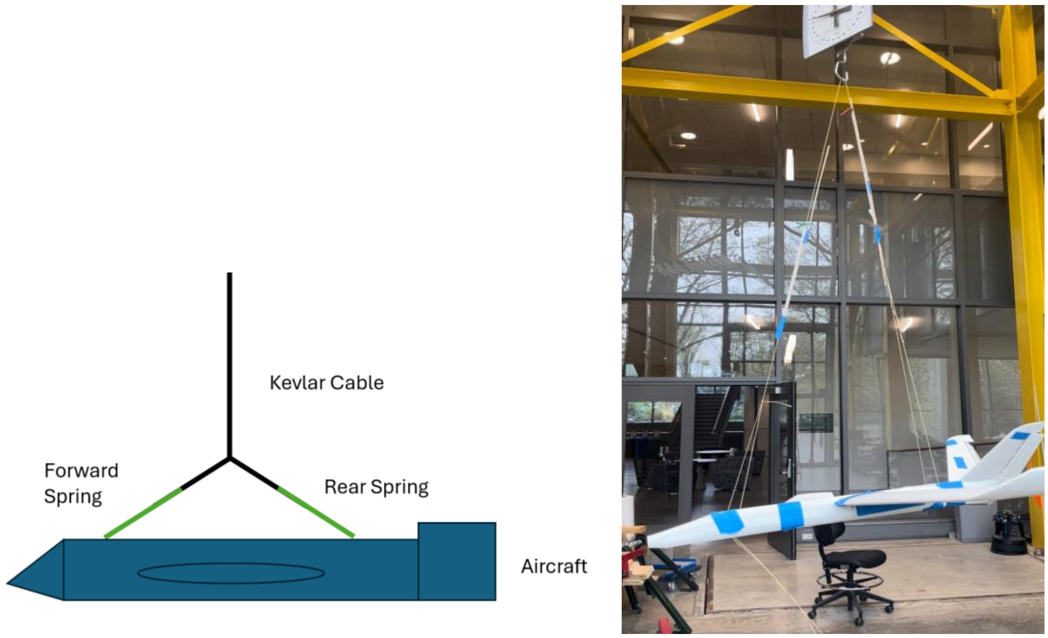


Figure 8 Open Wing Tunnel Setup

Using this wing tunnel setup I tested two aircraft. The Zohd GT Rebel[7] and compared its results to my own aircraft. The GT Rebel was chosen because it has the same control surface setup, weight package and propeller setup as my own. My results of the extension of the forward spring with full elevator controls being used is shown in Table 4.

Aircraft	String extension at full elevator (cm)	Force (F = kx) (N) k = 2 N/cm	Lift (N)
GT Rebel (Purchased Foam Aircraft)	~1.2	2.4	Negligible
3D Printed Aircraft	~0.5	1	Negligible

Table 4 Open Air Wind Tunnel Results

Interpreting the results, although expected, very little lift was experienced by either aircraft. This is because the airspeed of the wing tunnel of 5 m/s is still small and this generates negligible amounts of lift, because lift is proportional to velocity squared, and the original specifications of the lift off speed is 10 m/s. The results for the extension were done by varying the angle from the elevators from maximum (45 degrees) to minimum (-45 degrees), I, alongside E14 students recorded a 0.5 cm extension and contraction. This set of data indicates the elevators are producing some meaningful forces on the front and back of the aircraft. However, this is still not enough. In baseline testing with other aircraft with defined properties, we managed to measure average extensions of approximately 1 cm. This indicates that a traditional RC aircraft will produce double the pitching forces that we saw on this aircraft. This difference will also get exasperated as the wind speed increases and indicates that my current design is

[7] (ZOHD, 2024)

not robust enough to be controlled. Knowing this, I began doing simulations to discover why my aircraft was unable to be controlled.

Simulation

To avoid having to rebuild my aircraft during each test, I used computational fluid dynamics (CFD) to simulate the lift and drag of my aircraft. I used Autodesk CFD[8] that allows the visualization of the airflow dynamics around the aircraft. In the following figures, red indicates a higher velocity while blue and green indicate lower velocities.

The aircraft's CFD analysis is shown in Figure 9 and indicates the wake of the body around the wind tunnel. The parameters of the wind tunnel for this figure are a 0-degree angle of attack with incoming speed of 10 m/s. Interpreting the image, the image is a plane which shows the velocities of air passing the aircraft. Warm colors represent faster air, while cooler colors represent slower air.

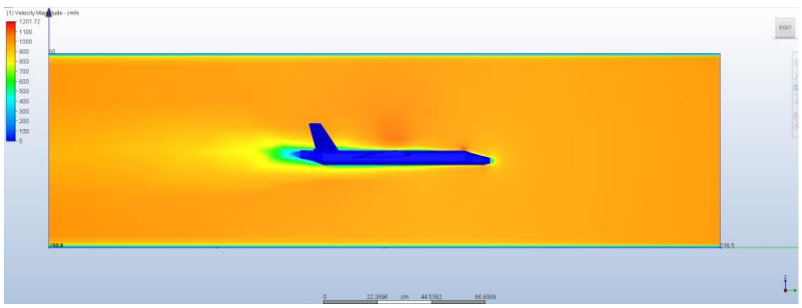


Figure 9 CFD Analysis of body profile.

Figure 9 shows what we would generally expect out of a body. We can see high velocity air at the top of the aircraft, and lower velocity air on the bottom of the aircraft. This corresponds to a pressure gradient with lower pressure at the top and higher pressure at the bottom aircraft. This is consistent with what is standardly expected of lift, as this pressure gradient causes the lifting phenomenon. The more interesting parts of this CFD study is that the wake of the body splits towards the tail section where lower velocity air impacts the tail. A zoomed in version of where the deflection occurs is shown in Figure 10.

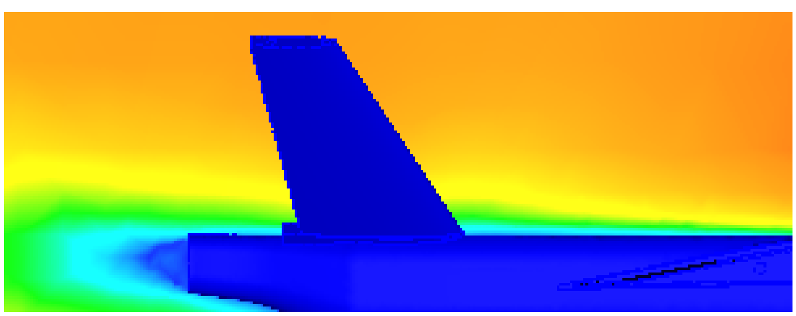


Figure 10 Wind Deflection at Tail

Figure 10 shows a zoomed in version of the previous CFD analysis. Inspecting the right of the image, the wind around the body is losing speed as compared to the baseline 10 m/s airflow.

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[8] (Autodesk, 2024)

More concretely the yellow indicates a 30% decrease in windspeed. This is more generally referred to as turbulence. This turbulence extends nearly halfway up the V tail and indicates that the tail components are not as effective as they could be. The current deflection angle which represents the angle that the disrupted air makes relative to the body is approximately 3 degrees. This deflection angle increases as the velocity of air and angle of attack increases. At a 5-degree angle of attack, the deflection angle doubles to 6 degrees. This indicates that due to some reason that causes the deflection it will eventually lead to a cascading failure in the airstream that will fully disrupt the capabilities of the V tail.

Finally, the CFD analysis also provides a summary of the forces that are affecting the aircraft. The summary forces on the aircraft states that the lift of this aircraft at a zero-degree angle of attack is 4.1N and this force is centered at approximately 7 cm from the leading edge of the wing. You will notice that this is a stark difference from the original lift prediction of 10N. This likely stems from the fact that the ideal airfoils do not simulate turbulence from the aircraft, nor from the edges of the wings. This is likely the main reason why the aircraft produces less lift. This is summarized in Table 5.

	Value
Lift at 0 Deg AOA	4.12 N
Lift at 5 Deg AOA	9.40 N
Center of Lift (0 Deg)	-7.01 cm
Deflection Angle	3-6 Deg
Weight	1.8 kg

Table 5 Summary of CFD Analysis

Flight Controller

The second phase of my project was to design a flight controller for my aircraft. I used an Arduino integrated with off the shelf ELRS receiver transmitter pairs. ELRS is a common transition protocol and I chose to use off the shelf components for the radio transmitter because it is difficult to design radio communication systems and that would take too long. This ELRS receiver, however, still must be decoded, and then actuate the control system to the four control surfaces of my aircraft. The block diagram in Figure 11 describes the general features of the controller.

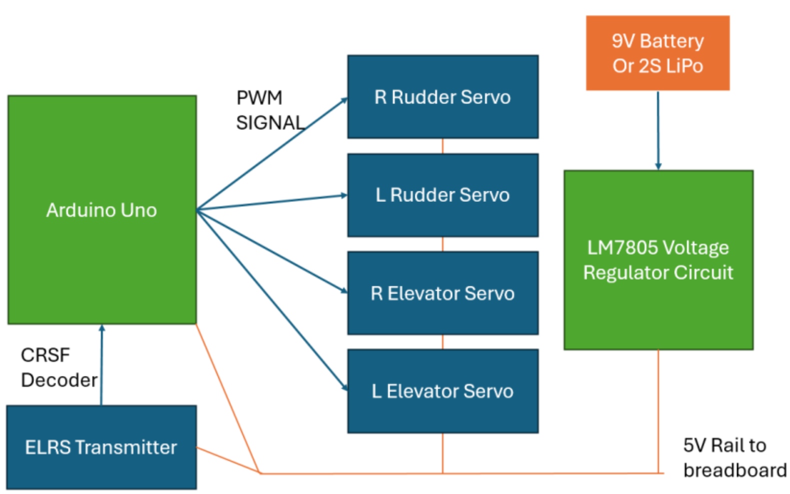

Figure 11 Block Diagram of Basic Controller Scheme

The reasoning behind the external power supply powered by the LM7805, is because the servos and ELRS transmitter draw too much current and the Arduino Uno is unable to pull that much power.

Final Design and Further Work

Improving on core design

Knowing that the current aircraft is unable to pitch correctly, I needed to perform another redesign. The likely reasoning behind the failure of the pitching force is that the nose off the aircraft is too long. A simplified force body is shown in Figure 12.

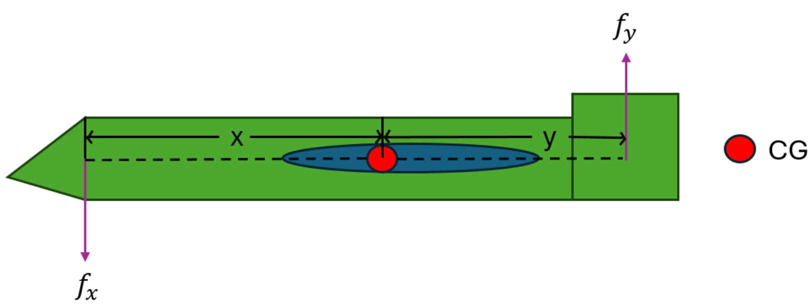

Figure 12 Basic Force Model

In Figure 12, we can simplify the moment around the CG to be $M = f_y y - f_x x$. The moment component from f_x, is multiplied by the distance x, and this causes a large moment to be generated. This reduces the effectiveness of the rear force, f_y and means that the elevators will not be able to pitch up or down the aircraft up or down as easily. To fix this problem, without changing the CG, we have to maintain a large mass towards the front of the aircraft, but reduce the moment arm it produces. This can be done by shortening the nose.

Next, to improve the deflection angle, a CFD analysis was conducted on the nose of the aircraft. The CFD analysis shown below indicates that the original nose design was the cause of the deflection. The original nose design's CFD analysis is shown as Figure 13.

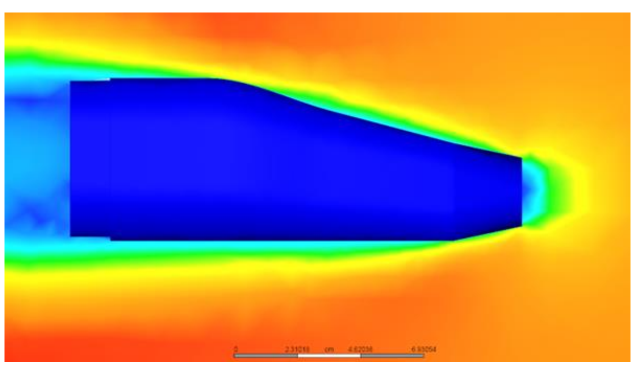

Figure 13 Original Nose

The original nose's CFD analysis shows that as soon as the noses curve ends and merges into a horizontal line, the deflection of the air does not follow the curve of the body but instead the deflection continues with a similar angle of the forward curve. This is likely because the air that impacts the nose is extremely fast and when the curve sharply evens back out the air is still travelling too fast to follow the body again. This means that by stubbing out the nose the air may have enough time to follow the nose again and not deflect out away from the body. A redesigned nose is shown in Figure 14.

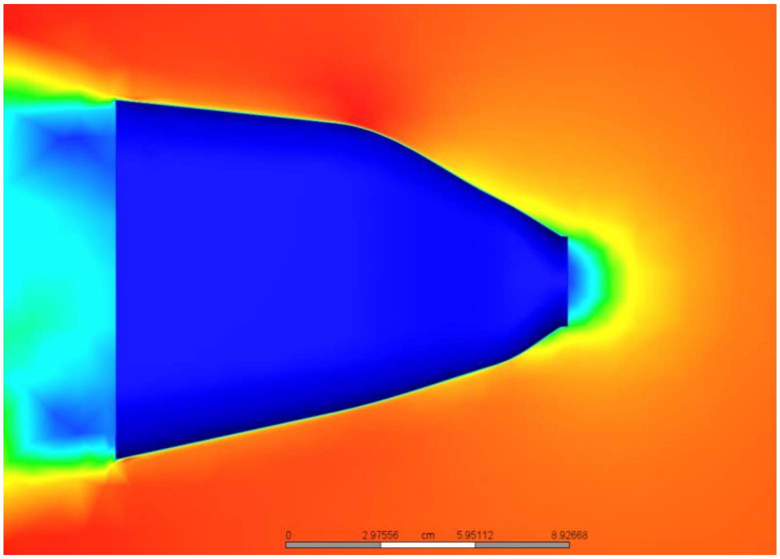

Figure 14 Redesigned Stubby Nose

The new CFD analysis shows that this stubbier nose has a better profile with no visible deflection occurring in the active region of the nose. The active region here is defined as where the solid body ends. This is because generally there's meant to be the body there and taking results past that point would not be accurate. This corrected the deflection problem. Combining these two fixes brings me to my final design. This design is realized in the following Figure 15.

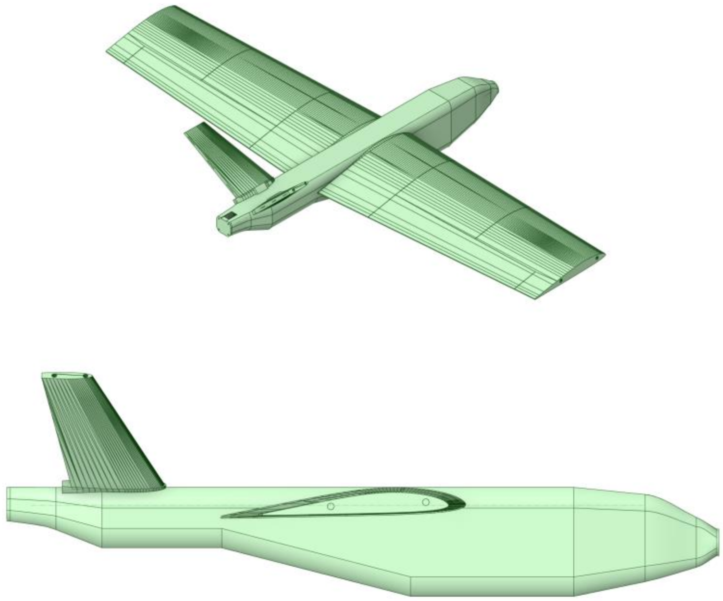

Figure 15 Large Body Design, Isometric and Side Profile

This body differs from the previous because the body begins to vertically thicken in the middle of the wing, and this reaches a maximum by the time wing ends. The side profiles show the new profile and I believe that this body will be able to not only archive higher lift, but also will improve the effectiveness of the elevators.

Simulations

Identical CFD tests were performed on the newest bodies. The same parameters were used, with 10m/s incoming wings and at a zero-degree angle of attack. The body profile is shown in Figure 16.

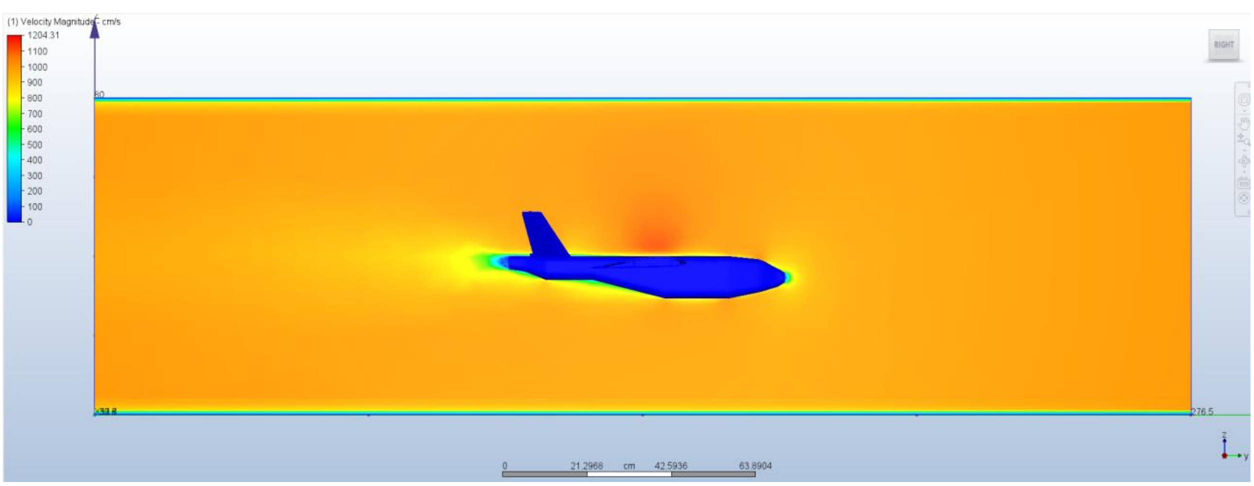

Figure 16 Body Profile

Figure 16 once again shows similar features to Figure 9, where high velocity airflows flow above the wing, and low velocity airflows flow below the wing. Notable differences however are that the wake of the airfoil does not interrupt the V tail section of the aircraft. It's likely that this new design will perform better than the old one just because of this. Further, the wake the aircraft generates is also less. This can be seen by the fact there are fewer and shorter green trails coming off the back of the aircraft. This indicates that the aircraft is visually more aerodynamic than the previous design. This is likely since spiked noses like the original aircraft cause air to deflect off the nose. The full results of the CFD analysis at both 0 and 5 degrees can also be shown in Table 6 where I compare this new iteration to the previous design.

	Original Aircraft	New/Modified Aircraft	Percent Change
Lift at 0 Deg AOA	4.12 N	4.32 N	4.8% ↑
Lift at 5 Deg AOA	9.40 N	9.82 N	4.5% ↑
Center of Lift (0 Deg)	-7.01 cm	-6.83 cm	2.5% ↑
Deflection Angle	3-6 Deg	1-2 Deg	50+% ↓
Weight	1.8 kg	~1.2 kg (Approximate)	33% ↓

Table 6 CFD analysis comparison

The comparison shows that the new aircraft outperforms the original aircraft even in areas where it should not such as lift and weight. However, this aircraft still maintains the same stability features as the original design. This final design should theoretically also be statically stable and should have the same capabilities, control scheme and performance as the original. Most of the changes are purely to solve deflection angles.

It is slightly interesting that we see increases in potential lift, and this is likely due to solving the turbulence problem coming from the nose. It is possible that the turbulence generated by the nose actually extended over the wings and this causes reduced lift and control in the original design. This problem was indirectly solved by the nose optimization.

Evaluation

This project had an initial design specification of wide proportions; however, the project specifications were not all met. The following shaded Table 7 dictates the constraints and requirements that I managed to meet. Green indicates a met goal, Red a failed goal, and yellow a partially met goal. I will discuss why I was unable to meet the other requirements.

Constraints	**Requirements**
Brushless Motor only contains 4N of thrust	Drone should fly for ~30 minutes
My maximum lift is constrained by wingspan which is subject to change	Needs to be thrown as no landing gear will be designed
Maximum flight ceiling of 90m to comply with flight authorities	Drone should be less than 2kg so that it does not injure someone on impact.

Battery capacity is sub 3000mAh	Center of gravity should lead center of pressure for maximum stability
Sub $400 cost	Drone should be stable during flight
	Drone should be robust and easily repaired
	Have a high enough velocity at throw that enough lift is generated by the wings. (Approximately 7 meters per second)

Table 7 Met Targets and Goals

I met the majority of the goals of my project. I stayed within the constraints of my project where I used the same brushless motor and battery as the start of the project and my maximum lift was still constrained by the wings. I also stayed within my $400 budget. I also designed effectively around ergonomics with the ability to throw my aircraft and land on a large flat body so that my aircraft does not get severely damaged on landing. However, the larger main failed objectives were since I was unable to completely test my aircraft.

I was unable to completely test the entire system because of time constraints and the hardest part of the project was testing the aircraft. This is because each time I tested the aircraft, it would crash, and the aircraft would shatter, and it took significant time to repair each iteration. This iterative process of fixing the aircraft was time consuming and I did not have enough time to keep on repairing the aircraft. This surprised me as this indicated that while I originally believed that LW-PLA would make aircraft easier to repair and more robust, 3D printed materials, while easy to obtain and use, are still not robust enough to survive catastrophic crashes. This limits the lifecycle of the components used and made repairs extremely costly.

Further, due to doing other flight tests where I attempted flying other foam aircraft which I purchased online, I realized that flying aircraft was an incredibly difficult task. Even using full off the shelf flight controllers and aircraft, many aircraft that I attempted to fly crashed nearly instantly. This combined with the significant cost of repairing LW-PLA led me to halt all flight tests on my 3D printed aircraft and focus on wind tunnel and simulations.

This leads to the failed goal where the aircraft would be robust and easily repaired. I initially underestimated the strength of light weight PLA and found it difficult for the aircraft to land or crash land without significant damage. The second condition I was unable to meet was the stability requirements. I was unable to determine the stability in a normal flight because I never flew the aircraft normally. This is likely because I could not tune the CG and CoP correctly which contributed to the stability failure. This lack of stability also led to the failure of the last requirement, where I could not test if the aircraft could fly for 30 minutes, as I did get that far in testing. However, under wind tunnel testing at sub 10 m/s speeds, the aircraft did behave extremely well where minor changes to the aircraft such as banking left and right automatically corrected itself.

All the other constraints and requirements were met though along with the basic functionality of the flight controller, which under wind tunnel testing performed just as expected and similar performance to a real flight controller.

Budget

Finally, the final constraint I had was the sub $400 cost. The cost of each individual component is listed below where it shows that I ended up under budget.

Item	Cost/Item	Quantity	Total Cost
LW-PLA Light weight PLA to print aircraft	32	2	64
Micro Servo MGS90 Servo to actuate control surfaces	28	1	28
Brushless Motor Motor for aircraft	20	1	20
Arduino Nano Arduino as embedded system to control aircraft	22	2	44
GPS Module GPS module for tracking aircraft	30	1	30
IMU Module Gyroscope module for implementing active stabilization	35	1	35
Transmitter ELRS Transmitter for RC control	60	1	60
Receiver ELRS Receiver for RC control	13	1	13
LiPo Battery (Large) Power for RC Receiver and Power for motor	26	2	52
LiPo Battery (Small) Power for Arduino	23	2	46
Net/Crash Pad			
Total	-	-	392

Table 8 Budget and Supplies

Table 8 budget and supplies, shows all the components I purchased and used for this project. These parts were used for design and construction of the model across all iterations.

Conclusion and Further Work

In the end, I had extensive goals, which I was unable to fully complete. However, I was able to effectively utilize LW-PLA and basic aerodynamic principles to develop three improved iterations of aircraft designs, each addressing specific challenges from previous versions. The iterative approach led to enhancements in lift, stability, and control mechanisms. Further, a proportional flight controller was engineered using an Arduino, only tested in controlled environments, and still requiring development in autopilot functionalities. I also developed a comprehensive testing regime, including both flight and wind tunnel testing, and have been instrumental in refining the aircraft designs. Future efforts will focus on further testing and refinement, aiming to integrate advanced control features and expand the testing scenarios to ensure the aircraft's reliability and performance in more conditions.

This project has much room for further improvements. I was only able to produce a proof of concept that iterated upon many design challenges. However, for future work it’s possible for someone to use the designs I made to produce an aircraft. Next it is also possible for a student with more experience flying aircraft to integrate my flight controller design into the aircraft as well. Further once the aircraft is tested, it could be time to begin testing with a remote sensing payload. This could be as simple as a visual camera but as complex as multispectral or infrared cameras. Once this occurs I believe the true vision of my project can be considered as completed.

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