May 15th, 2017

Final Report

Oklahoma State University – NACA Know How

2017 Aircraft Design Competition

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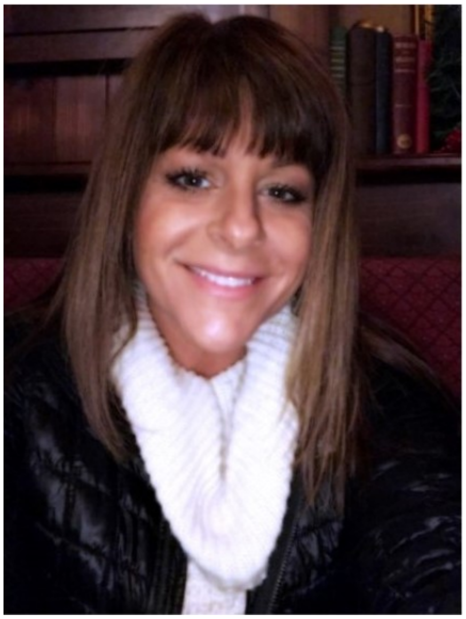
Meet NACA Know How

Lucas Utley

Team Lead, Propulsion

Hometown: Little Rock, AR

Bio: Loves all things rockets, major Elon Musk fanboy. Hiking and swimming are favorite pastimes. Aspiring engineer in the private spaceflight industry. Hopes to buy a Tesla and never has to drive it.



Danielle McLean

Configurator, Market Researcher, Propulsion

Hometown: Tulsa, OK

Bio: Interests include anything to do with space travel, music production and playing piano, politics, craft beer, and heath and fitness.

Ultimate career goal: Innovate the future of aerospace engineering, whether it be SpaceX, Boeing, a smaller company, or eventually starting her own company.

Brandon Whitney

Capture Manager, Aerodynamics, Structures

Hometown: Katy, Texas

Bio: Interests include sports, backpacking anywhere, music and design. Career goal is to work for Lockheed Martin working on missiles. Fun fact: has hiked the four highest peaks in Texas (picture to the left is atop of one of them).

Meet NACA Know How

Jake Rosario

CAD/Graphics, Systems & Avionics

Hometown: Guthrie, OK

Bio: Interests include any sports, designing/building things, the outdoors, and spending time with family and friends. Ultimate career goal is to be a successful aerospace engineer at a reputable company like SpaceX. Personal fun fact: races open-wheel sprintcars and midgets in free time.

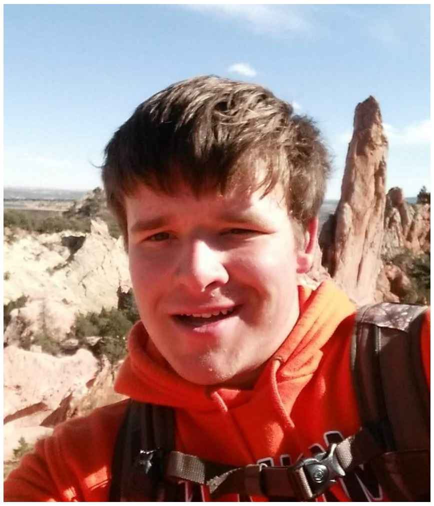
Bret Valenzuela

Aerodynamics Team Lead, Structures

Hometown: Edmond, OK

Bio: Interests include all things basketball, building computers, rock climbing/hiking, longboarding, watching film, and convincing people that Chacos are the perfect sport sandal. Researcher for Dr. Elbing in the Experimental Fluid Physics Lab.

Looking to pursue a master's degree in aerospace engineering, move on to work for a reputable company doing propulsion engineering. Owns 2 cats but the bigger is the youngest. Also collects NBA t-shirts.



Reid Williams

Systems & Avionics Team Lead, Aerodynamics

Hometown: Plano, TX

Bio: Junior Mechanical and Aerospace Engineering major. Loves rockets, race cars, and planes. Hopes to one day work for an aircraft company, but if money were no object, would start his own racing team.

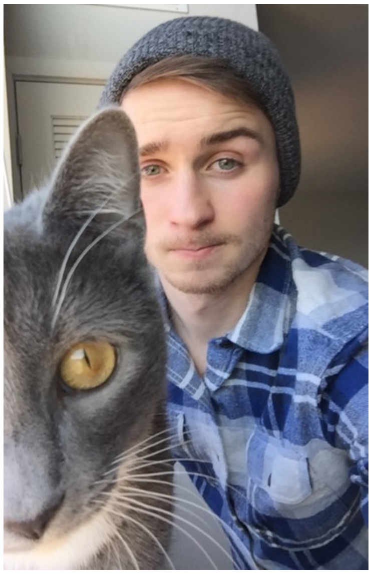
Meet NACA Know How

Andrew Walsh

Structures Team Lead, Aerodynamics

Hometown: Bixby, OK

Bio: Loves sports, rockets, and chicken. Career goal is to not be a subordinate engineer.



Brendan Disque

Propulsion Team Lead

Hometown: Wylie, TX

Bio: Anything that involves the outdoors, will most likely try at least once. Camping, kayaking, rock climbing, and backpacking are all hobbies and looking to get back into wrestling/MMA.. Ultimate Career Goal: Does not want to be stuck in a rut, as we tend to do as people. Looking to get into aerospace and defense now, but one day may want to switch out to privatized .

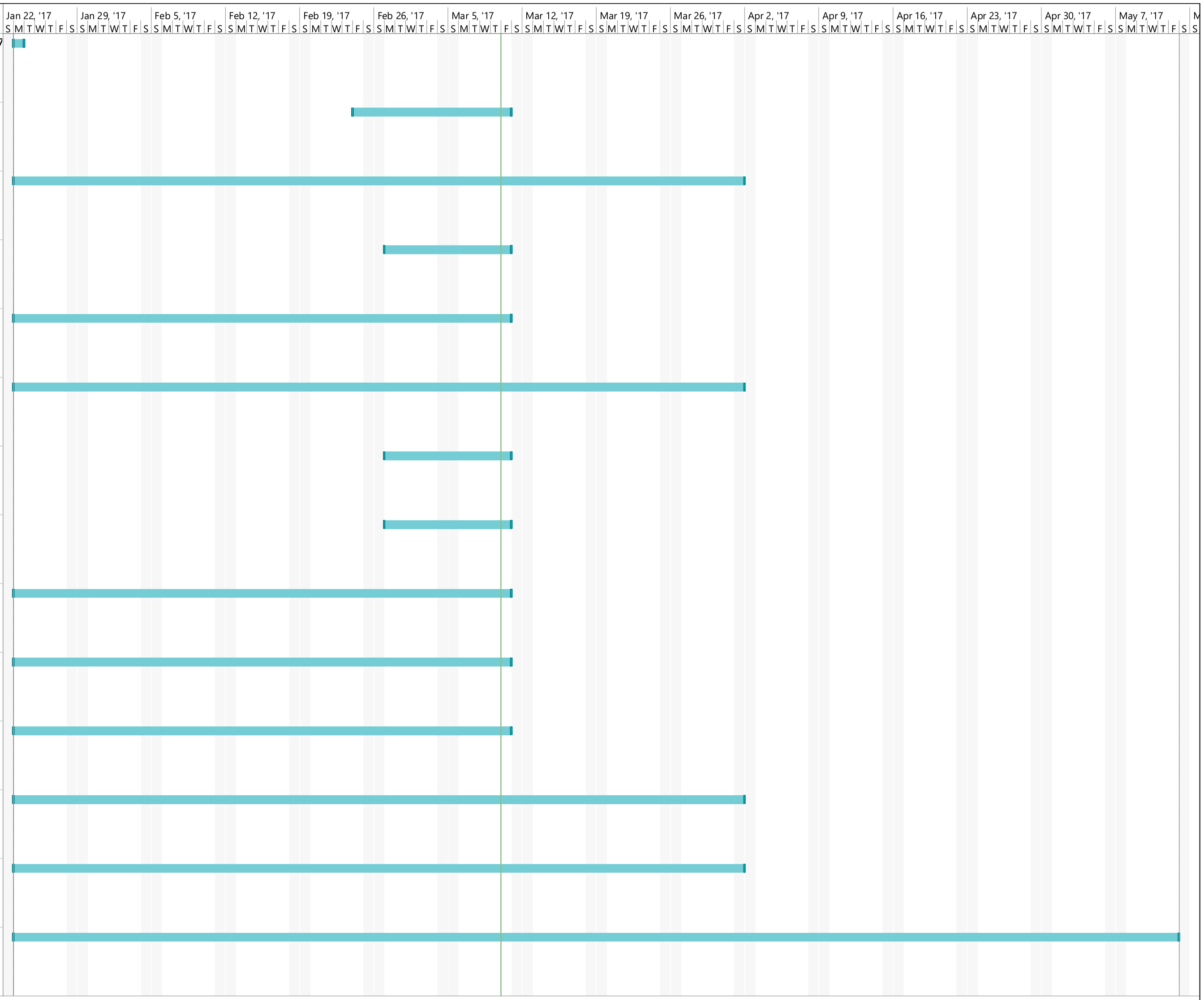
Nicholas Foster

Propulsion, Systems & Avionics

Hometown: Edmond, OK

Bio: First year senior working to complete dual degrees in mechanical and aerospace engineering with minors in mathematics and Spanish. Plans to get his masters in aerospace engineering before moving into industry. Interests include spacecraft GNC, rocket propulsion and unmanned aerial systems. In his free time he enjoys playing disc golf.

ID	ℹ	Task Mode	Task Name	Duration	Start	Finish
1		📌	Project Start	1 day	Mon 1/23/17	Mon 1/23/17
2		📌	Progress Report 1	11 days	Fri 2/24/17	Fri 3/10/17
3		📌	Airfoil Design	51 days	Mon 1/23/17	Sat 4/1/17
4		📌	Market Analysis	10 days	Mon 2/27/17	Fri 3/10/17
5		📌	Benchmarking	35 days	Mon 1/23/17	Fri 3/10/17
6		📌	Engine decision	51 days	Mon 1/23/17	Sat 4/1/17
7		📌	Trade study & design downselect	10 days	Mon 2/27/17	Fri 3/10/17
8		📌	CONOPS	10 days	Mon 2/27/17	Fri 3/10/17
9		📌	Mission Profile	35 days	Mon 1/23/17	Fri 3/10/17
10		📌	Initial Weight Sizing and Constraint Analysis	35 days	Mon 1/23/17	Fri 3/10/17
11		📌	Design Options	35 days	Mon 1/23/17	Fri 3/10/17
12		📌	Materilal Selection	51 days	Mon 1/23/17	Sat 4/1/17
13		📌	Avionics Selection	51 days	Mon 1/23/17	Sat 4/1/17
14		📌	Final Report	80 days	Mon 1/23/17	Fri 5/12/17



Project: naca know how gantt

Task
Split
Milestone ◆
Summary
Project Summary
Inactive Task
Inactive Milestone ◇
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only [
Finish-only]
External Tasks
External Milestone ◆
Deadline ⬇
Progress
Manual Progress

Executive Summary

For 2017's Aircraft Design Competition for Applied Aerodynamics and Performance at Oklahoma State University, NACA Know-How designed a hydrogen-powered autonomous aircraft that provides internet coverage from the air.

This year's objective was focused upon increasing internet availability to ground locations where internet access may be expensive, slow, or unreliable. Mission requirements included takeoff and landing from a standard runway, support for one hundred kilograms of internet-providing payload, sustained flight of one week, and an approximate cruise altitude of 60,000 feet. Due to the high altitude and lengthy flight time, efficiency on all aircraft aspects were to be maximized.

Solar power generation, battery energy storage, and electric motors were involved NACA Know-How's first attempt at sustained flight in excess of one week. After multiple design iterations of propulsion, structures, and aerodynamics, the team determined that with today's technology in solar panel efficiency and weight, battery energy density and weight, and electric motor output, there was no feasible way to fly such an aircraft through the night with the given mission profile requirements.

To explore other options, NACA Know-How found a promising solution involving an internal combustion engine, modified for hydrogen fuel and compressed air oxidizer. This configuration presented several challenges, primarily in redesigning the fuselage and structural layout, but the power consumption rate was optimal and allowed flight times greatly over one week.

With this new propulsion system, all mission requirements were successfully met.

Mission Objectives

NACA Know How is developing a High Altitude Long Endurance (HALE) aircraft, *FlyP Address*, which will provide internet capability to certain ground regions around the world. Minimum mission requirements include the following: takeoff and landing from a standard runway, support for 100 kilograms (221 pounds) of internet-providing payload, approximate operational altitude of 60,000 feet, and sustained flight of one week.

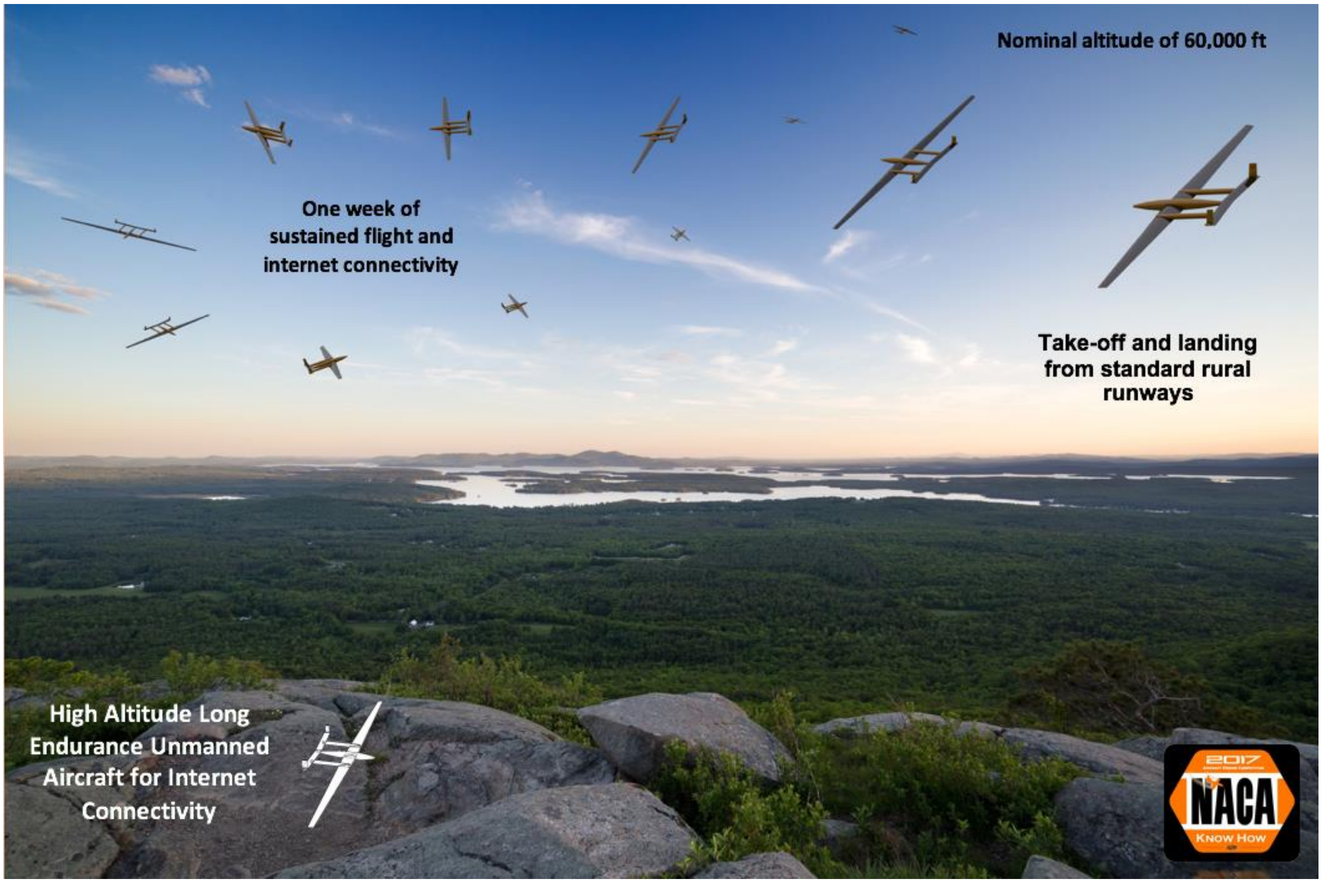


Figure 1.1: CONOPS

To achieve multiple days of continuous flight, a high-efficiency, turbocharged internal combustion engine has been modified to run on liquid hydrogen and compressed air oxidizer. This design outperforms any combination of solar cells, batteries, and electric motors and provides the necessary propulsion and endurance to maintain flight in excess of one week.

The design involves powered ascent, cruise, and low-power descent upon exhaustion of hydrogen fuel. The extended mission duration allows for increased flexibility in the event of bad weather (inhibits takeoff or landing), mission profile adjustments, and additional needed internet provision.

Due to a relatively low cruise speed, NACA Know How is designing this aircraft to be self-sustaining and can spend multiple days travelling on its own to the (remote) target location, carry out the mission objective of internet provision, and return to an airport for maintenance while another aircraft takes its place.

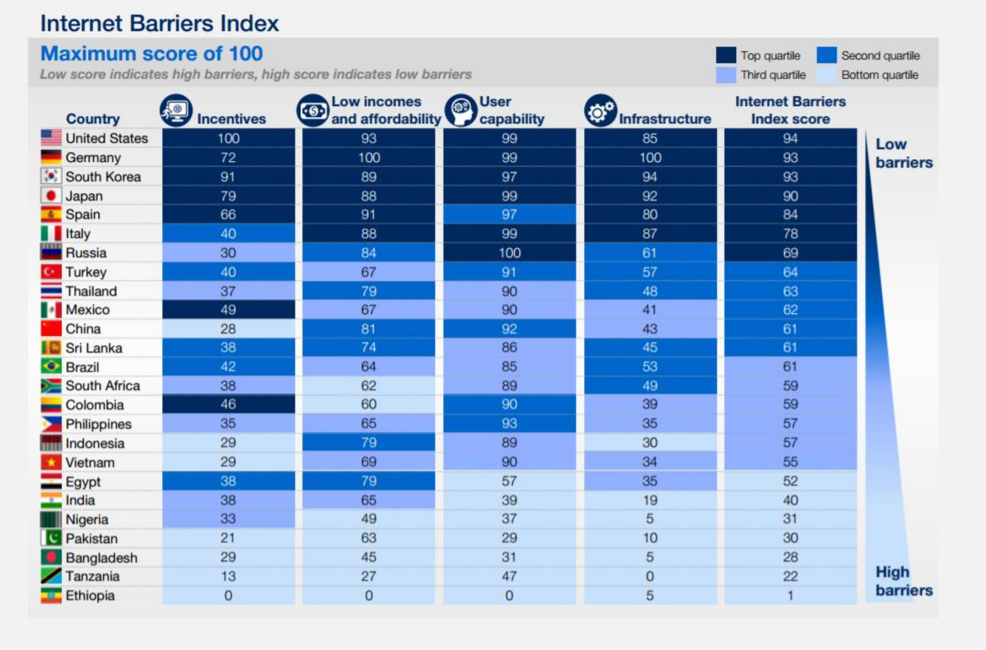
The drive for extended flight time is the intention to provide internet to regions of the world that currently lack reliable high-speed internet. From the air, an established network of these autonomous, ultra-efficient aircraft will provide ample internet coverage to remote areas in developing countries.

Figure 1.2: FlyP Address *with landing gear configuration*

Projected Customer Profile

Of the four billion people across the globe who do not have access to internet, three billion are living in just twenty countries (Mckinsey and Company, 2014). Some of these locations have restricted internet due to government regulations, yet many do not have internet because their geographical location make it physically impossible or unaffordable. NACA Know How intends to target locations that could readily benefit from airborne internet access.

Mckinsey and Company, a worldwide management consulting firm, did an extensive study in 2014 that broke down areas without internet and the barriers that they face. NACA Know How uses this data to select ideal customers in countries with an Internet Barrier Index score of fifty to seventy as seen below.



Internet Barriers Index

Maximum score of 100

Low score indicates high barriers, high score indicates low barriers

Top quartile
Second quartile
Third quartile
Bottom quartile

Country	Incentives	Low incomes and affordability	User capability	Infrastructure	Internet Barriers Index score
United States	100	93	99	85	94
Germany	72	100	99	100	93
South Korea	91	89	97	94	93
Japan	79	88	99	92	90
Spain	66	91	97	80	84
Italy	40	88	99	87	78
Russia	30	84	100	61	69
Turkey	40	67	91	57	64
Thailand	37	79	90	48	63
Mexico	49	67	90	41	62
China	28	81	92	43	61
Sri Lanka	38	74	86	45	61
Brazil	42	64	85	53	61
South Africa	38	62	89	49	59
Colombia	46	60	90	39	59
Philippines	35	65	93	35	57
Indonesia	29	79	89	30	57
Vietnam	29	69	90	34	55
Egypt	38	79	57	35	52
India	38	65	39	19	40
Nigeria	33	49	37	5	31
Pakistan	21	63	29	10	30
Bangladesh	29	45	31	5	28
Tanzania	13	27	47	0	22
Ethiopia	0	0	0	5	1

Low barriers

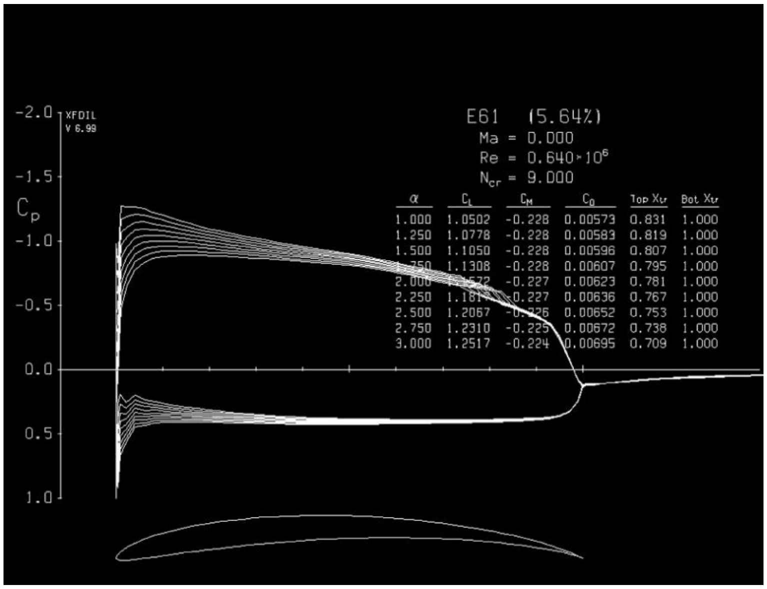
High barriers

Figure 1.3: Table of internet barriers index (Offline and Falling Behind, 2017)

Aerodynamic Analysis

Airfoil Selection and Analysis

FlyP Address' airfoils were selected using preset parameters, iterative analysis, and structural considerations. The airfoils needed to have high C_l/C_d value while keeping realistically low C_d's. Early on, the aerodynamics team decided that it would be highly beneficial to use two different airfoils in the wing. This was primarily to allow for a thick, and therefore structurally strong, airfoil for the base and then choose a more efficient, thinner airfoil for the rest of the wing. The next step was to search for airfoils that would be highly efficient at a Reynolds number of 1,000,000. Unfortunately, the most efficient airfoils at this Reynolds number tend to be very thin, eliminating them from the selection process. The aerodynamics team decided to pick the most efficient airfoil with a thickness of over 7% of the chord; this led to the selection of the FX 76-MP-120. This airfoil gave the team an acceptable C_l/C_d. While the drag is inherently higher, this airfoil proves its worth by being large enough to hold internal structures. XFOIL was used to analyze all airfoils in the form below:



E61 (5.64%)

$Ma = 0.000$

$Re = 0.640 \cdot 10^6$

$N_{cr} = 9.000$

α	C_L	C_M	C_D	Top X_{tr}	Bot X_{tr}
1.000	1.0502	-0.228	0.00573	0.831	1.000
1.250	1.0778	-0.228	0.00583	0.819	1.000
1.500	1.1050	-0.228	0.00596	0.807	1.000
1.750	1.1308	-0.228	0.00607	0.795	1.000
2.000	1.1572	-0.227	0.00623	0.781	1.000
2.250	1.181[illegible]	-0.227	0.00636	0.767	1.000
2.500	1.2067	-0.226	0.00652	0.753	1.000
2.750	1.2310	-0.225	0.00672	0.738	1.000
3.000	1.2517	-0.224	0.00695	0.709	1.000

Figure 2.1: XFOIL airfoil analysis

Below are the performance numbers pulled from XFOIL using the ‘PWRT’ function to print values. All airfoils were analyzed using viscid condition at Re=1,000,000.

Resulting Polars

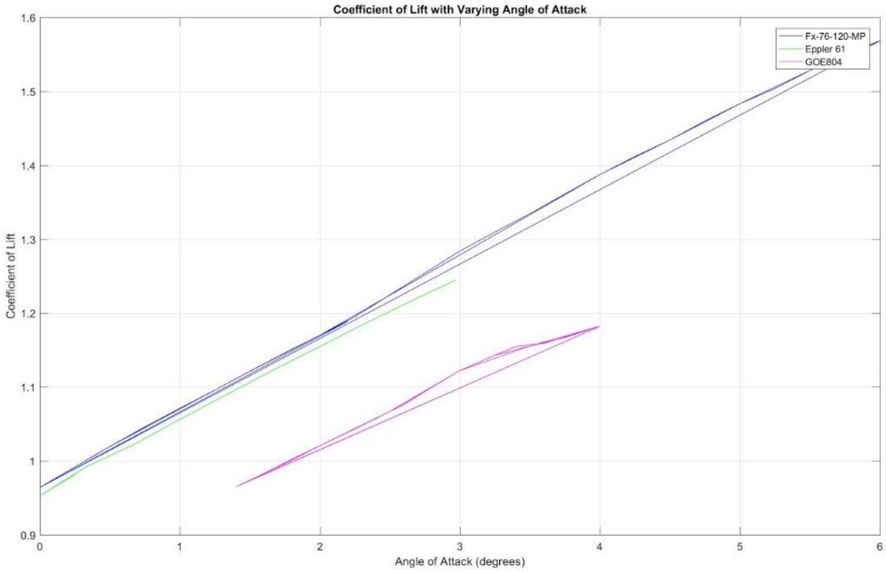


Figure 2.2: Lift coefficient vs angle of attack for three select airfoils

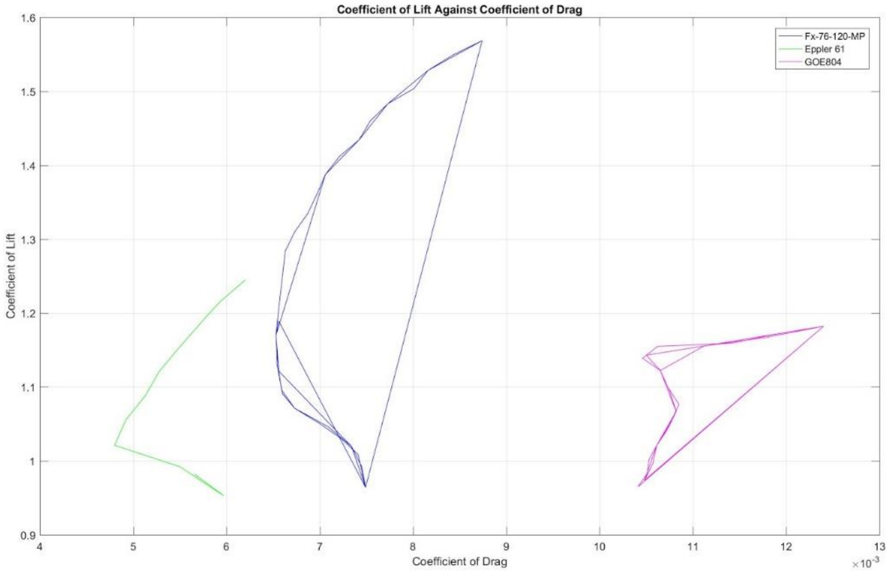


Figure 2.3: Lift coefficient vs drag coefficient for three select airfoils

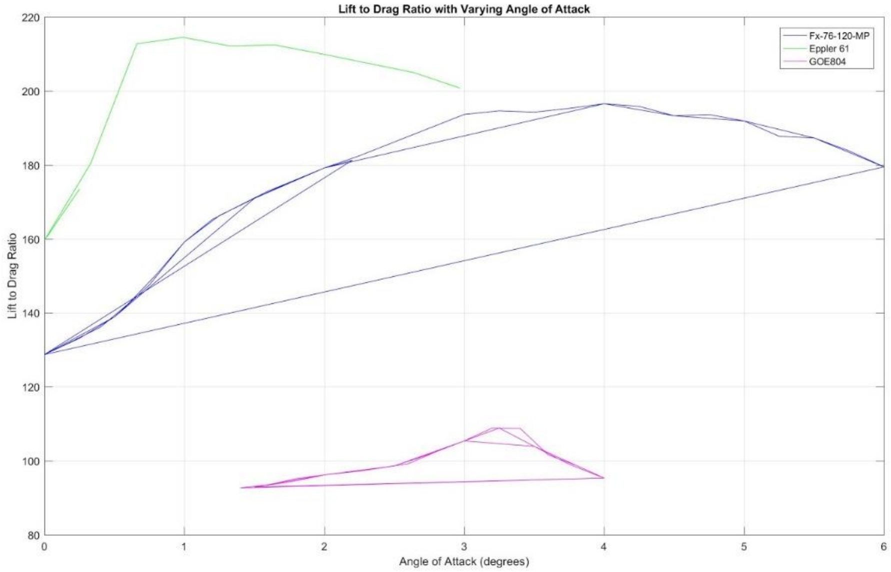


Figure 2.4: L/D vs angle of attack for three select airfoils

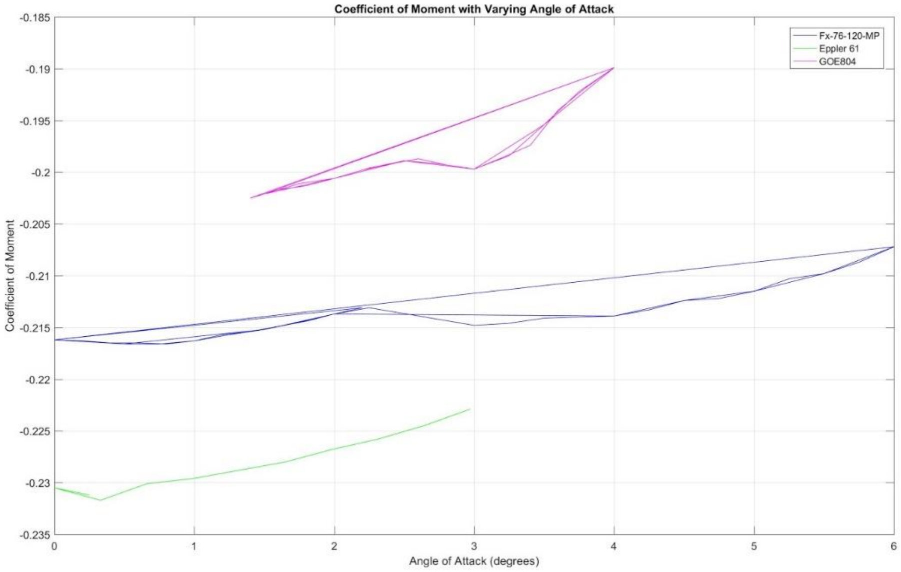


Figure 2.5: C_M vs angle of attack for three select airfoils

The FX 76-MP-120 obtains a max C_l/C_d of 196.5439 at an angle of attack of 4 degrees. Once this airfoil was selected the team turned its attention to selecting a thinner, more efficient airfoil. The airfoil still needed to be thick enough to support the internal structures of the wing, so it was determined that the team could not pick an airfoil that had less than 5.5% thickness of chord. After searching for the most efficient airfoil at this minimum thickness, the aerodynamics team selected the Eppler 61 for its performance at Re=1,000,000.

The Eppler 61 airfoil obtains a max C_l/C_d of 214.5112 at an angle of attack of 1 degree. These two airfoils gave the FlyP Address' wing a stellar C_L of 1.063 at cruise as well as a C_L/C_D of 45.31. Both of these parameters are three dimensional and were analyzed using XFLR.

The last two orders of business in regard to airfoils were to pick the airfoils for the horizontal and vertical tail sections. For the vertical tail section, a symmetric airfoil is needed; the first decision point was to keep it simple and go with a well-known airfoil, the NACA 0012. The horizontal airfoil proved a little more challenging as FlyP Address needed a certain C_l to balance the aircraft. After searching for high C_l at high angles of attack, the aerodynamics team selected the GOE 804 (EA 8) airfoil. The GOE 804 clocked a C_L/C_D of 108.891 at an angle of attack of 3.2 degrees.

Wing Sizing

The primary driving factor behind the wing sizing was the benchmarking the NACA Know How team performed. It was clear that the common theme between high altitude long endurance aircraft was the very high aspect ratios. Based around the numbers of multiple HALE aircraft it was decided to land at an aspect ratio between 15 and 25. This would ensure that we had a large lift distribution and C_L/C_D and therefore increase our aerodynamic efficiency. This criteria meant we needed a large span with a small mean chord. Initial sizing out the span at 160 ft, but this proved to be too heavy and overall unmanageable. The aerodynamic team scaled the span back to 120 feet and decided to taper the wing to save weight. After consulting with Dr. Jacob the decision was also made to sweep the wing to move the aerodynamic center further back, making the aircraft more stable. The final wing parameters and the analysis thereof are shown below where 'Effective' denotes the values with the winglets:

Span = 120 ft.

$\text{Span}_{\text{Effective}}$ = 142.093 ft.

Root Chord = 10 ft.

Tip Chord = 4 ft

$\text{Tip Chord}_{\text{Effective}}$ = 2 ft.

Taper Ratio = $C_R/C_T = 10/4 = 2.5$

$\text{Taper Ratio}_{\text{Effective}} = C_R/C_{TEff} = 10/2 = 5$

Sweep Angle = $\Lambda_{LE} = 15°$

Mean Aerodynamic Chord = MAC = 8.196 ft.

Wing Area = S = 1075.336 ft.^2

$\text{Wing Area}_{\text{Effective}} = S_{Eff}$ = 1133.621 ft.^2

Aspect Ratio = AR = $b_{Eff}^2/S_{Eff} = 17.81$

Wing area, MAC, and all 'Effective' values were obtained using XFLR5. These wing parameters gave *FlyP Address* an excellent aspect ratio and optimized the position of our aerodynamic center.

Given the amount of wing modifications made by the aerodynamics team in the name of efficiency, the results of the XFLR5 test were promising. Exact data plot is shown below:

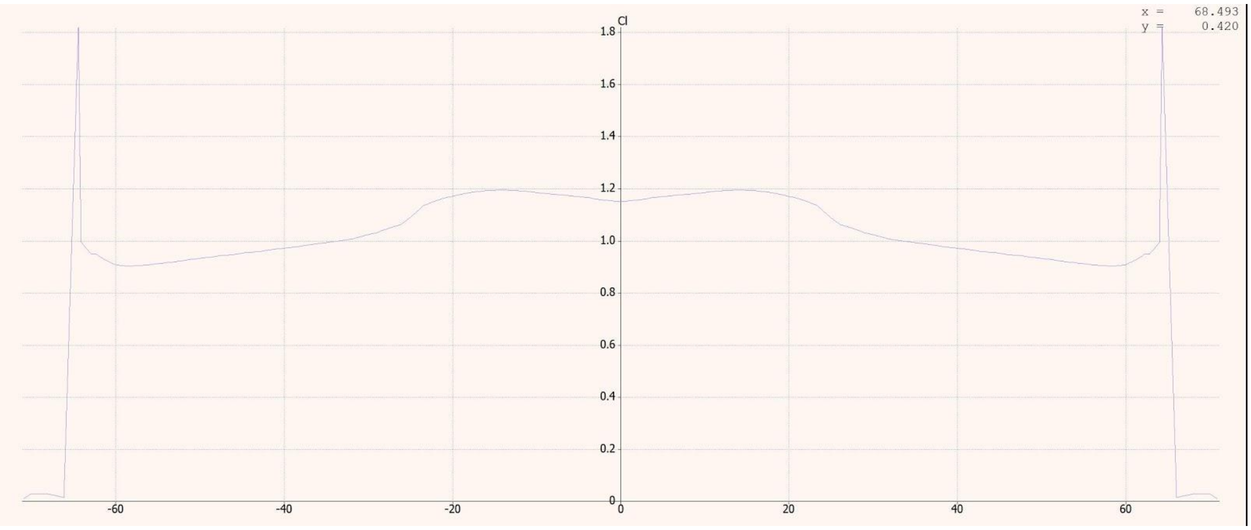


Figure 2.6: Lift distribution along wing

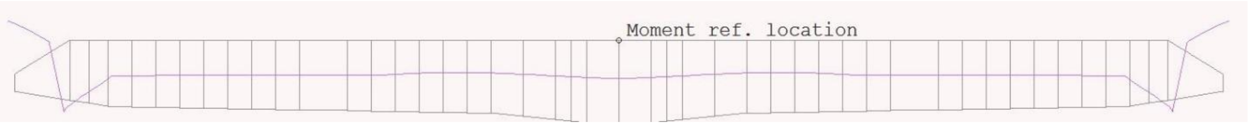


Figure 2.7: Moment distribution along wing

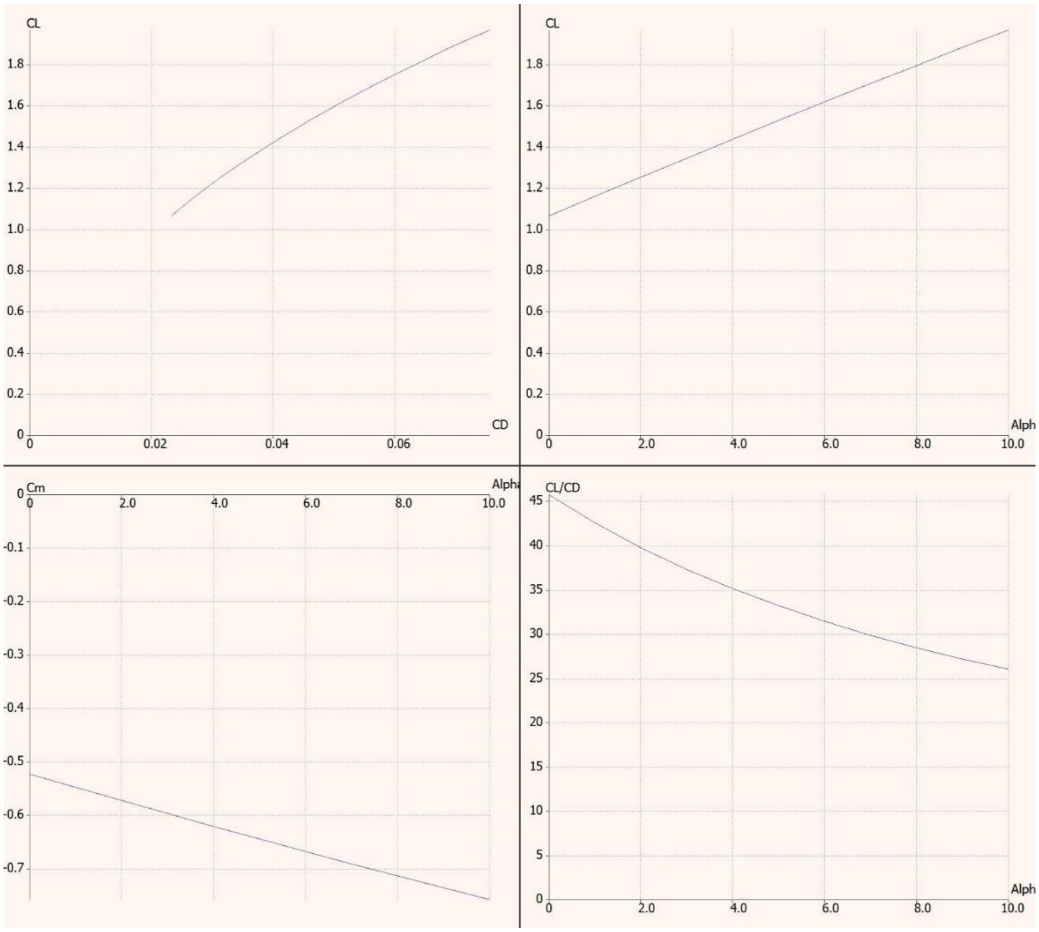


Figure 2.8: Polars

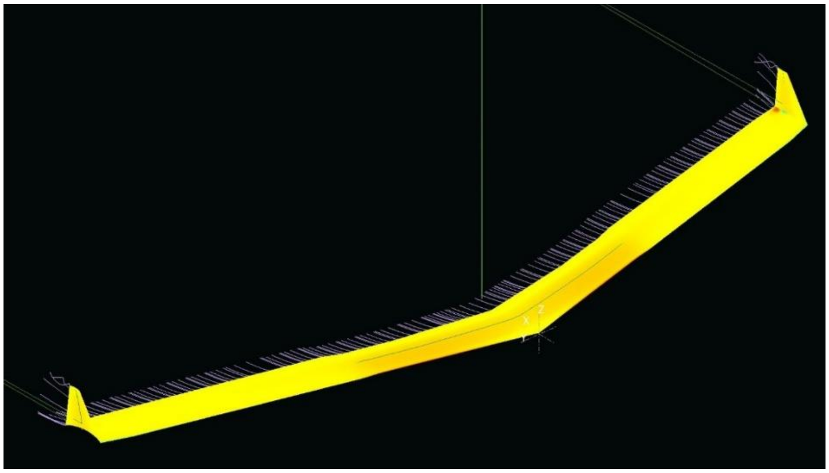


Figure 2.9: Stream and wing view

Planform Selection

Below is the planform of *FlyP Address*:

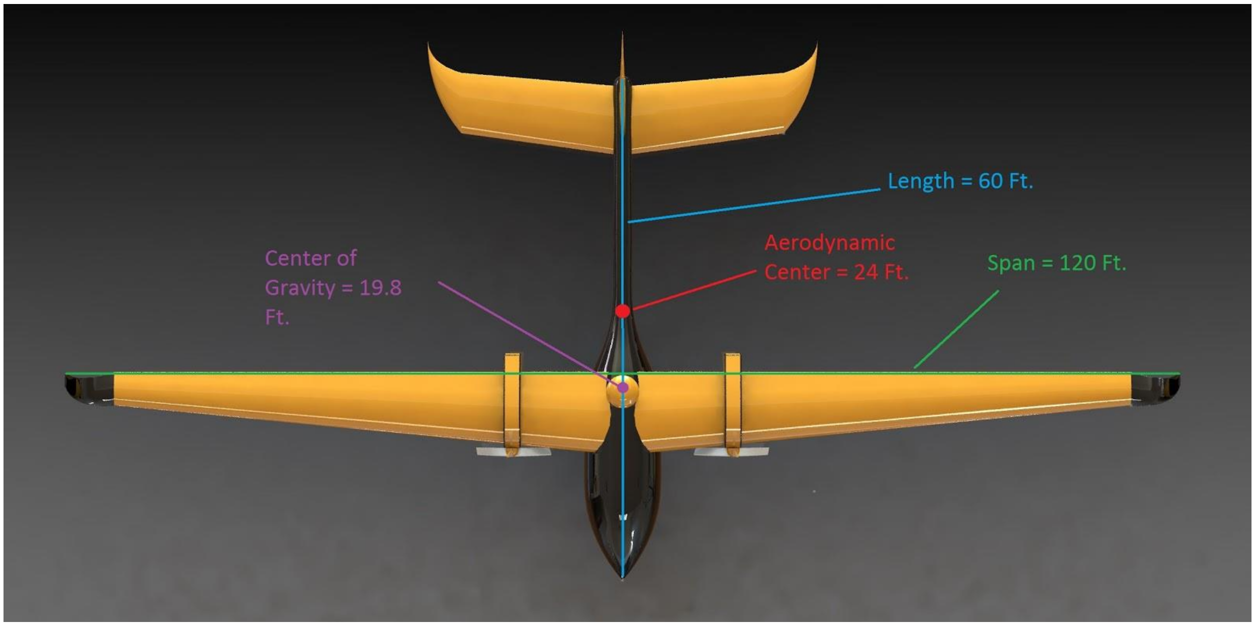


Figure 2.10: Planform view with labeled dimensions

The length of the entire aircraft came out to 60 feet with the center of gravity being just ahead of the aerodynamic center. It is also worth noting that when completely unloaded, *FlyP Address*'s center of gravity still falls two feet in front of the aerodynamic center.

Drag Buildup

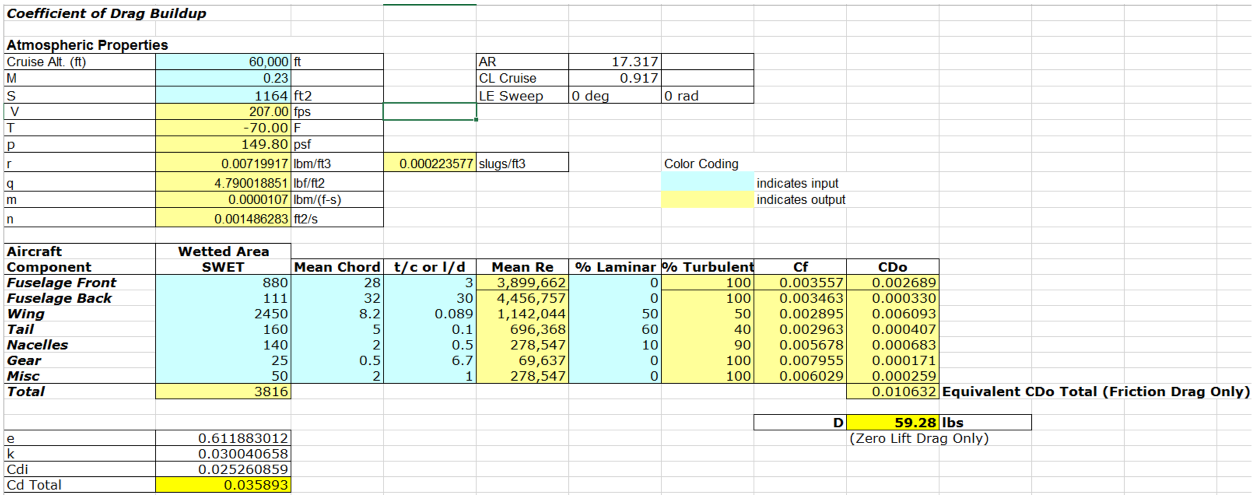
The aircraft will primarily be cruising at 100 feet per second at an altitude of 60,000 feet. During normal flight no flaps will be deployed and the plane will be in level and steady flight. Because of the low speeds *FlyP Address* will be experiencing, wave drag and Mach corrections are being neglected in the drag calculations. As such, the drag on *FlyP Address* can be broken up into two main components: parasite drag which is solely from the obstruction of airflow across the plane, and induced drag which is from the lift produced by the wings.

First, the total C_{D0} was calculated using the friction drag spreadsheet Dr. Jacob provided. This sheet uses a combination of flight conditions and plane areas to give an approximation of the zero lift drag. The total C_{D0} in designed cruise conditions is approximately 0.0106. The induced drag was calculated utilizing the equations:

$$C_{Di} = kC_L{}^2$$

$$k = \frac{1}{(\pi A R e_0)} \qquad e_0 = 4.6(1 - 0.33AR^{0.53})cos(\Lambda_{LE})^{0.3} - 3.3$$

The calculated C_{Di} at cruise condition came out to be 0.0253. Then from the equation $C_D = C_{Di} + C_{D0}$, the final C_D for cruise is 0.0359.



Coefficient of Drag Buildup

Atmospheric Properties

Cruise Alt. (ft)	60,000	ft		AR	17.317		
M	0.23			CL Cruise	0.917		
S	1164	ft2		LE Sweep	0 deg	0 rad	
V	207.00	fps					
T	-70.00	F					
p	149.80	psf					
r	0.00719917	lbm/ft3	0.000223577	slugs/ft3		Color Coding	
q	4.790018851	lbf/ft2				🟦	indicates input
m	0.0000107	lbm/(f-s)				🟨	indicates output
n	0.001486283	ft2/s					

Aircraft Component	Wetted Area SWET	Mean Chord	t/c or l/d	Mean Re	% Laminar	% Turbulent	Cf	CDo	
Fuselage Front	880	28	3	3,899,662	0	100	0.003557	0.002689	
Fuselage Back	111	32	30	4,456,757	0	100	0.003463	0.000330	
Wing	2450	8.2	0.089	1,142,044	50	50	0.002895	0.006093	
Tail	160	5	0.1	696,368	60	40	0.002963	0.000407	
Nacelles	140	2	0.5	278,547	10	90	0.005678	0.000683	
Gear	25	0.5	6.7	69,637	0	100	0.007955	0.000171	
Misc	50	2	1	278,547	0	100	0.006029	0.000259	
Total	3816							0.010632	**Equivalent CDo Total (Friction Drag Only)**
							D	**59.28**	**lbs**
								(Zero Lift Drag Only)	

e	0.611883012
k	0.030040658
Cdi	0.025260859
Cd Total	0.035893

Spreadsheet 2.1: Coefficient of drag buildup

High Lift Devices

FlyP Address is already a plane with low wing loading that flies at low speeds, so not many high lift devices are needed for the plane to be operational. The high lift devices consist of four slats and two flaps. Two slats and the flaps are located at the largest chord length of the wing allowing the highest lift portion of the wing to receive the effect of these devices. These spoilers will be located mid chord of the main wing.

For functionality, the slats energize the top boundary layer delaying separation. This allows for higher angles of attack at the cost of drag. These devices most likely never be used independently. The flaps function by increasing the camber of the airfoil. This increases the coefficients of lift at the cost of drag. Again these devices will most likely never operate independently.

The slats and spoilers have simple designs. The slats (as pictured below on a similar wing shape) will be attached at the leading edge of the wing with the ability to deploy at multiple angles.

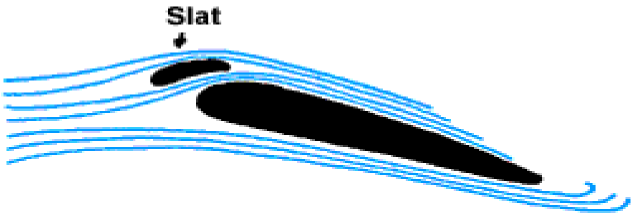


Figure 2.11: Wing slat schematic as used to increase lift (Jacob, 2017)

The flap design will be a simple plain flap design (pictured below) and would can deploy at multiple angles. While the design might not be the most efficient flap, it would be lighter and cheaper to manufacture. Flaps are not as critical of an element as it would be on other aircrafts so a simpler design is allowable.

Figure 2.12: Flap configuration for increasing lift (Jacob, 2017)

High lift devices would not be used for most of the flight of *FlyP Address*. They would be used for takeoff, landing, and emergency maneuvers. *FlyP Address*' would utilize the flaps and slats at various angles for takeoff and initial ascent. Once at higher altitude and more towards cruising speed the devices would retract. Flaps and slats would see use during landing to allow for lower approach speeds.

Propulsion Analysis

Solar power was the initial energy source for this aircraft. The reason behind this decision was the fact that it must keep aloft for a minimum of seven days. While most internal combustion engine-driven planes can keep flight for several hours, this form of propulsion would not come close to providing the necessary flight time for this mission. Making the plane solar powered was a great idea, but it contained some major issues. One being that with solar panels one can only generate power during daylight hours. There is also the added effect of the sun's angle incident to the solar panel. At higher altitudes, there is a loss in efficiency and during the winter season, there is more nighttime than daytime. This means one must carry enough batteries to power electronic systems, payload functionality, and maintain altitude. With the number of engines and electrical devices needing power, the battery weight became too large. Another issue is that over time the batteries would lose their capacity due to degradation of the battery. Replacing the batteries every five years would prove costly.

Following extensive online research, an uncommon option for propulsion is hydrogen power. Using liquid hydrogen fuel to burn in a converted supercharged car engine appeared promising. While fuel, tanks, and the engines are heavier than electric motors, batteries, and the necessary solar panels, the weight of the hydrogen propulsion system provides the power to not only remain aloft at altitude, but also the endurance to fly through the night and for multiple days after that. Where electric propulsion could only sustain battery-powered flight for several hours, this option of hydrogen power is more than sufficient to fly for days on end. When burning fuel, weight decreases over time and reduces fuel consumption associated with carrying a constant weight throughout, such as carrying useless weight of the drained batteries. This benefits the plane by making it lighter and thus could use less power and throttle back later on as the plane continues to fly. Boeing had a design where they tested a similar concept. It was able to carry a 1000 to 2500 pound payload up to 10 days. Their design was to fly at higher altitudes similar to this design.

As seen in Figure 2.1 below, liquid hydrogen is extremely energy dense and thus why it is attractive as a gasoline alternative in both cars and aircraft. The obvious problem with using liquid hydrogen as a source of fuel is that it is highly volatile and thus cannot be stored in areas such as the wings like in conventional aircraft. The alternative solution is to store the fuel in large spherical tanks in the fuselage of the aircraft. For manned aircraft, this can be an unnecessary risk with little performance gain. However, in unmanned aircraft this can prove to be a viable solution especially for long endurance missions.

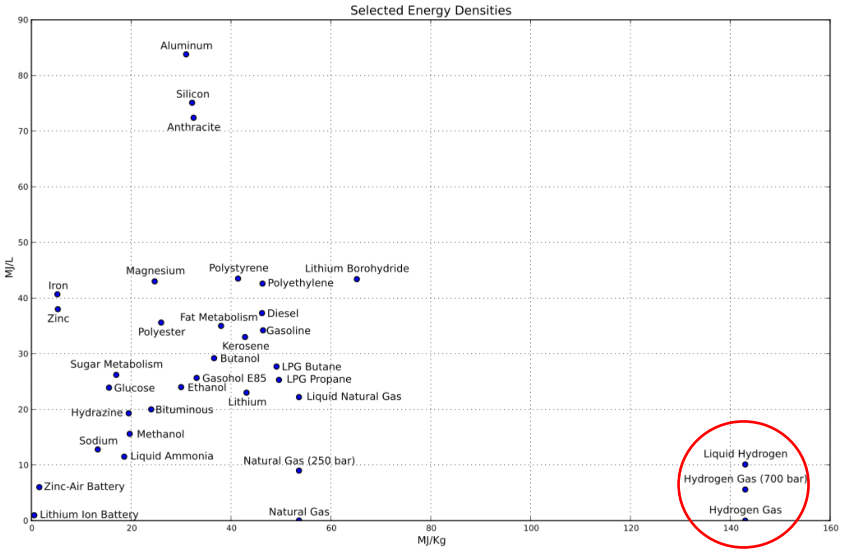


Figure 3.1: Energy density diagram for various substances (Dial, 2008)

Hydrogen internal combustion engines are not a new technology and in fact, the first internal combustion engine, designed by Francois Isaac de Rivaz, ran on a hydrogen/oxygen mixture (Eckermann, 2011)**.** Boeing proved the possibility of converting a Ford H2 engine into an aircraft engine with the creation of the Phantom Eye. However, the Ford H2 is not the only recent hydrogen internal combustion engine to be built. BMW tested the *Hydrogen 7* as a luxury car in 2005 as well as the futuristic *BMW H2R*, Mazda produced the *RX-8,* and even an Aston Martin *Rapide S* used a hydrogen internal combustion engine during the 24-hour Nurburgring race in 2014 (Paula, 2013). Due to the limited information on the specifics of these engines and their performance as a converted aircraft engine, NACA Know How decided to base its computations off the Ford H2 used in the Phantom Eye.

To sustain operation and maintain flight for consecutive days there must be extensive quantities of hydrogen fuel available. This is why the design has two eight-foot diameter tanks made of carbon fiber. Following the volume of a sphere, with eight feet of diameter (assuming a thin-walled pressure vessel), yields 268 ft^3 of contained liquid hydrogen and 268 ft^3 of stored compressed air. SpaceX has made fuel tanks out of carbon fiber for its rockets. To store cryogenic fuels, a substantial amount of insulation must be included into the tank's design and integration inside the fuselage.

At a design altitude of 60,000 feet the atmosphere is not especially dense, and there is insufficient oxygen to maintain engine combustion. To combat this issue, a turbocharger forces additional air into the system to burn the fuel at the optimal design rate to maintain constant altitude. The turbocharger, in junction with compressed air tanks, allows the engines to receive a steady flow of oxygen as the aircraft ascends and eventually descends through the atmosphere and through varying levels of air density and oxygen content. This setup requires alternators, insulating firewall, exhaust system, and batteries. While these additional components continue to add weight, the complete system still outperforms existing alternatives.

Propelling *FlyP Address* is high efficiency propeller blades. Due to the low density of air, some special considerations were made when selecting the number of propellers and the overall dimensions. This design works with three propellers per engine each being sixty inches long by twelve inches wide and an efficiency of 90-95%.

As per the design, there are two engines that each provide 150 horsepower. This gives 300 horsepower available for flight. The power required is 263 horsepower at altitude, so there is plenty to spare for climb and maneuvers. For the thrust required to keep steady level flight the drag force is 713 lbs. To calculate the thrust available, convert 300 horsepower to ft-lb/s then divide by the flight speed. This comes out to 813 pounds of thrust available.

Propeller Design

There are three main types of propellers. Fixed pitch, constant speed, and variable pitch. It is clear that the fixed pitch and speed cannot be as efficient as the variable pitch, so NACA Know How decided to choose a variable pitch propeller to maximize our aerodynamic efficiency and thrust available. NACA Know How then used the below equation to size the propeller.

$$D = \sqrt{\frac{T^3}{589\left(\frac{\rho}{\rho_{SL}}\right)P_s^2 N^{1/3}}}$$

Where D is the diameter of the propeller, T is the thrust required, P is the supplied power, and N is the number of blades. NACA Know How decided to select a 3 blade design to get max efficiency while minimizing weight and material. Using these parameters the propeller diameter was determined to be 8.6 feet.

Structural Analysis

The structural design of Fly-P Address is imperative to both a successful flight and the safety of people on the ground. In order to ensure these ideals are met certain things must be considered from the beginning of the design phase. This includes structural analysis and careful consideration of weights throughout the plane.

Materials Survey and Selection

The most import decision that needed to be made was what materials to use. Traditionally aluminum alloys such as Al 7075 have been used in aircraft construction due to the high strength and fatigue resistance (Mraz, 2017). The main downside, however, is the weight. As seen in Figure 3.1, Aluminum 7075 has a density of 172.9 pound per cubic foot which normally would be sufficient but for a hydrogen-powered HALE aircraft, every gram counts. Because of this, the structures team has decided to explore alternatives such as carbon fiber, fiberglass, Kevlar/epoxy, foam, and aircraft fabric. These materials were selected from our benchmarking of similar vehicles in which we found the NASA Helios and Airbus Zephyr used them (Dunbar, 2015).

Carbon fiber is a promising material with many of its properties having an advantage over aluminum. Its density is roughly 96.74 pound per cubic foot which is roughly half that of aluminum. Weight isn’t the only advantage, however. The yield strength of carbon fiber is 170 kips per square inch compared to 70 kips per square inch of aluminum 7075. The problem with CFRP though is that it’s a unidirectional strong material. While in one orientation it can hold up to very large loading, in almost any other direction it's significantly weaker. Additionally, it doesn't hold up to nicks and cuts well and once it's been damaged the member weakens significantly. Also worth noting is that carbon fiber parts are expensive and difficult to produce on a large scale without defects. Boeing found this out with their extensive manufacturing problems on the 787 (Birch, 2004). Some of these effects can be mitigated by reinforcement from other materials but it is worth considering.

Fiberglass is another promising composite due to its high yield strength of around 60 kips per square inch. This is comparable aluminum 7075, but not as high as carbon fiber. The tradeoff in strength is made up for with its higher levels of flexibility allowing it to be used in instances where loads are not unidirectional. Additionally it's cheaper and easier to manufacture than carbon fiber (Carbon Fiber vs Fiberglass, 2017). The density of fiberglass comes out to be 111.75 pound per cubic foot which makes it slightly lighter than aluminum 7075 but much heavier than carbon fiber. These tradeoffs are worth noting, but it just doesn’t seem to be worthwhile compared to carbon fiber.

Kevlar with epoxy is most comparable to CFRP. They are both composites with similar densities, but Kevlar has a slightly lower yield strength. The unidirectional downsides of carbon fiber still exist in Kevlar though. Something of note from the structures team research though was that on the Helios, it seems NASA chose to reinforce their spars on the Helios using Kevlar (Dunbar, 2015). NASA’s reason for doing so was to stiffen and reinforce the wing for structural integrity. This application is worth considering for the final design.

Fiberglass-reinforced foam has many potential uses on *FlyP Address*. Its lightweight nature affords for many possibilities with non-load bearing parts. For example NASA used it in the wing tips of the Helios. The structures team will also investigate its usage in other areas of the wing as well as in the fuselage. Additionally, foam that is fire retardant could make for a good insulator around batteries and engine components to prevent heat or fire damage to the composites if an emergency happens.

Aircraft fabric is another promising material for *FlyP Address*. It is used to cover the outside of planes to provide an aerodynamically favorable surface. It can't be used to support much weight, but instead acts as a thin skin. The density of aircraft fabric is only 55.97 pound per cubic foot making it an ideal lightweight material. If it were to be wrapped around a barebones internal skeleton it could provide substantial weight savings to the aircraft over conventional outer coverings like aluminum and composites.

	Density (lb/ft^3)	Yield Strength (ksi)	Elongation at Break (%)	Shear Strength (ksi)	Cost ($/lb)
Al 7075 - T6	172.9	70	11	48	7.15
Kevlar/epoxy	86.17	160	2.4	NA	9.92
CFRP	96.74	170	2.03	9.4	47.4
Foam	25.92	NA	NA	0.32	NA
Fiberglass	111.75	60	4.8	NA	8
Oratex Aircraft Fabric	55.97	0.0239	15	0.0239	NA

Table 4.1: Aircraft material properties

The major problem faced by the structures team was making the plane as light as possible in order to optimize flight endurance. This is definitely a task that's easier said than done. Some of the challenges of materials consideration are cost of raw materials and manufacturing, weight, and workability.

At first glance, the best option is to use carbon fiber for everything. With a relatively low density and high strength there is a reason many companies such a Boeing are making the switch from more traditional materials. For these reasons the structures team has preliminarily chosen to make all internal components with carbon fiber. After doing more research into manufacturing processes, the structures team discovered some difficulties in using it too extensively. For one, there is not a lot of research on it that other materials such as metals possess. It is also not an easy thing to mass produce or to use in large objects. All these factors would contribute to making the plane exponentially more expensive than using cheaper alternative materials. As such, before the final report is submitted the structures team will continue investigating the viability of incorporating more common materials into the structural design.

For the skin of the plane, the structures team has settled on using aircraft fabric, specifically Oratex6000. It is a lightweight material than can be formed to all the odd shapes of the plane relatively easily. It is also a comparatively cheap material allowing for the structures team to cut down on some of the manufacturing costs. The Oratex website advertises the ability to cover a small plane for $4,000.

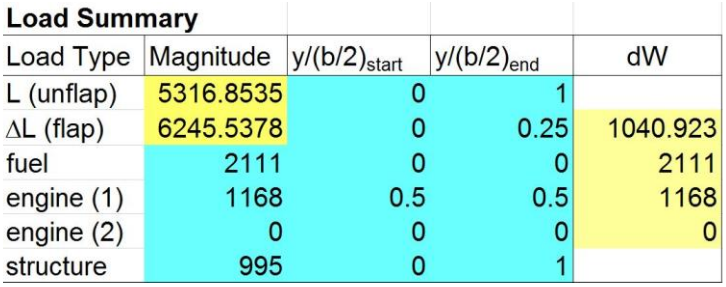
Primary Structural Loads

NACA Know How understood the importance of the structural load from the very beginning of this design. The structural loading and the analysis of that loading is arguably the most important aspect of the aircraft. NACA Know How’s structures team decided to use the ‘LOADS.xlsx’ sheet provided by Dr. Jacob to assist in the calculations of the loads and the distributions of those loads. Parameters entered into the ‘LOADS’ spreadsheet are shown below. The parameters will be discussed and then the results presented.

Wing

Wing and Weight Data

GTOW	7042	lbs
S	1134	ft^2
A	17.8	
Λ_{LE}	15	deg
λ	0.90	
CLmax	1.958	No Flaps
ΔCLmax	2.3	W/ Flaps
n	1.51	Load Factor



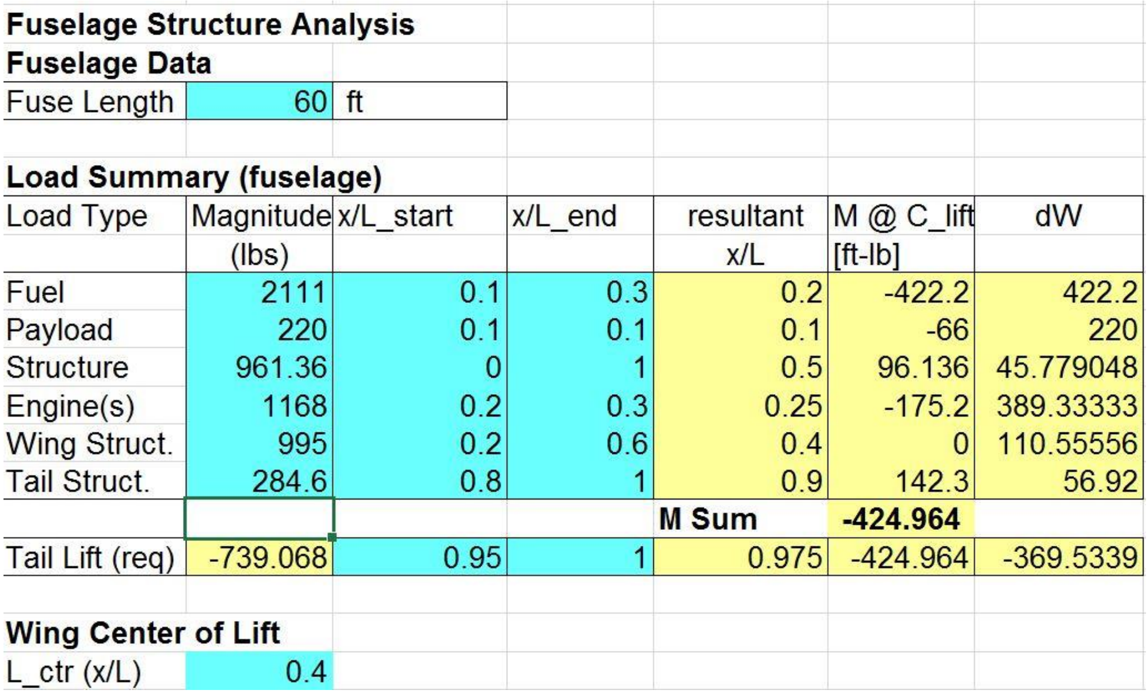
Load Summary

Load Type	Magnitude	$y/(b/2)_{start}$	$y/(b/2)_{end}$	dW
L (unflap)	5316.8535	0	1	
ΔL (flap)	6245.5378	0	0.25	1040.923
fuel	2111	0	0	2111
engine (1)	1168	0.5	0.5	1168
engine (2)	0	0	0	0
structure	995	0	1	

Spreadsheet 4.1: Wing loading data

Obvious parameters aside, the structures team decided to use a load factor of 1.5 since the design load factor is going to be low on this type of aircraft. The load factor was increased to 1.5 from 0.5 to account for a safety factor. It is worth noting that both the fuel and engine (2) are zeroed out. This is because *FlyP Address* does not carry fuel in the wings and only has two wing-mounted engines.

Fuselage



Fuselage Structure Analysis

Fuselage Data

Fuse Length	60	ft

Load Summary (fuselage)

Load Type	Magnitude (lbs)	x/L_start	x/L_end	resultant x/L	M @ C_lift [ft-lb]	dW
Fuel	2111	0.1	0.3	0.2	-422.2	422.2
Payload	220	0.1	0.1	0.1	-66	220
Structure	961.36	0	1	0.5	96.136	45.779048
Engine(s)	1168	0.2	0.3	0.25	-175.2	389.33333
Wing Struct.	995	0.2	0.6	0.4	0	110.55556
Tail Struct.	284.6	0.8	1	0.9	142.3	56.92
				M Sum	**-424.964**	
Tail Lift (req)	-739.068	0.95	1	0.975	-424.964	-369.5339

Wing Center of Lift

L_ctr (x/L)	0.4

Spreadsheet 4.2: Structural Analysis (Fuselage)

All values, aside from the length of the aircraft, were obtained from NACA Know How's 'SWAP'. This allowed the structures team to accurately describe the loads in the fuselage. The results of both the wing and fuselage analysis are shown below:

Wing

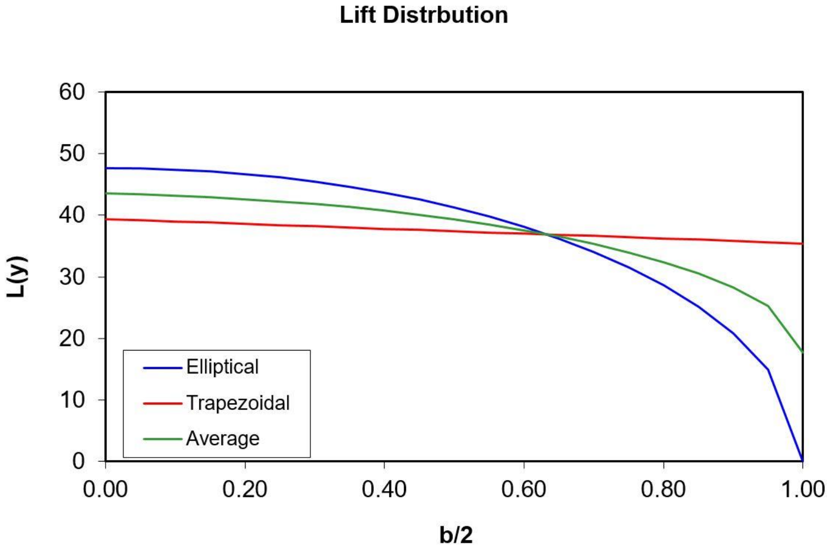


Figure 4.2: Load (aerodynamic) and moment distribution

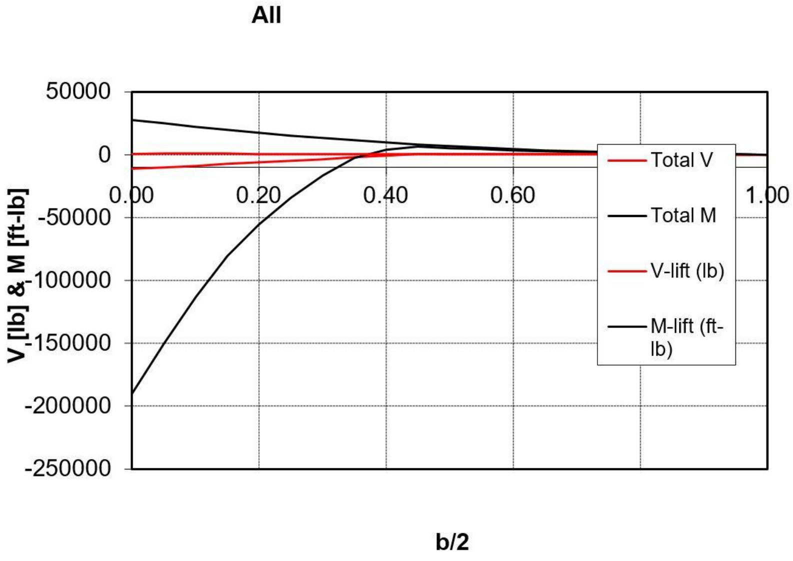


Figure 4.4: Total load and moment distribution

Fuselage

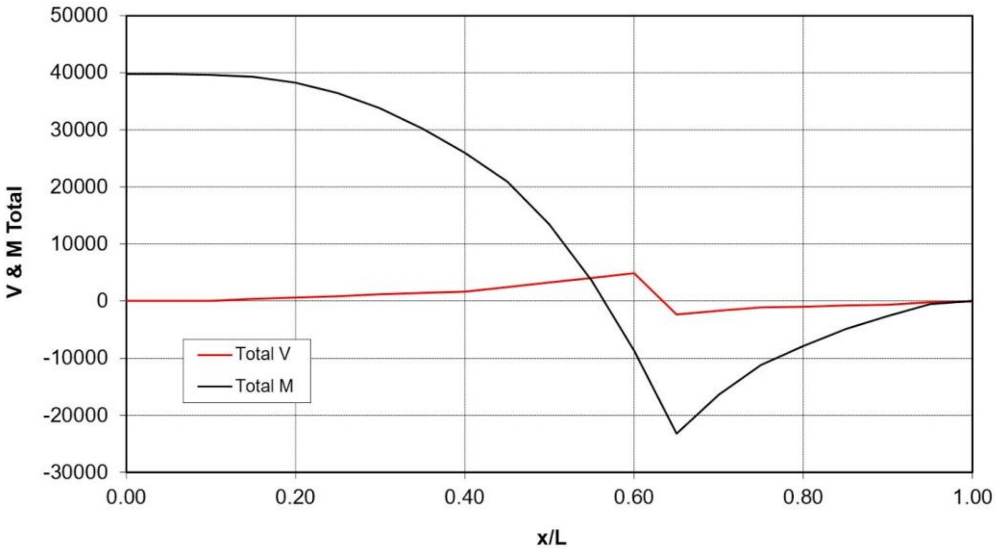


Figure 4.5: Load and moment distribution

As is shown in the above data, *FlyP Address*' on board loads are relatively high. This meant that NACA Know How had to plan for both a strong internal structure and an internally well designed wing.

Structural Design Concept

Figure 4.6: Internal structures view

Figure 4.6 is shows the three-dimensional structural design model of *FlyP Address*. Initially, when the company was going to use solar panels and batteries to power the plane, the structures group had decided to use Mylar for the exterior of the full plane. This was chosen because it is a similar material to that of the underside of the NASA Helios, which is a transparent and lightweight material so that the sun can get to the solar panels. After much deliberation and many calculations, the propulsion group decided to move away from solar panels and batteries to hydrogen power. This relieved the structures team of having to use the transparent Mylar material and allowed the team to make the entire exterior of the plane aircraft fabric, namely Oratex 6000. Inside the wings there are ribs, which are the grey airfoils, every sixteen inches which have the same shape as the airfoil at the root of the wing, an FX-76. The spacing between the ribs was chosen from benchmarking similar aircraft whose span is similar to the size of FlyP Address. These ribs are made of carbon fiber which was also chosen based on similar aircraft. The ribs mainly provide buckling stability and also help keep the airfoil shape so that when the aircraft fabric is stretched over these ribs it holds the right shape for the wing.

The other structural aspect of the wing are the two spars that run from the tip through the entire span of each wing, which are the purple structures. The spars were chosen to be square in shape with an outside diameter of four inches. The spars were chosen to be cylindrical with an outside diameter of four inches. These spars are made of carbon fiber and run through two holes in each of the ribs. In each stabilizer there are two spars made of carbon fiber. These spars are used to take on aircraft loads and transfer it to the fuselage so as not to break the wing.

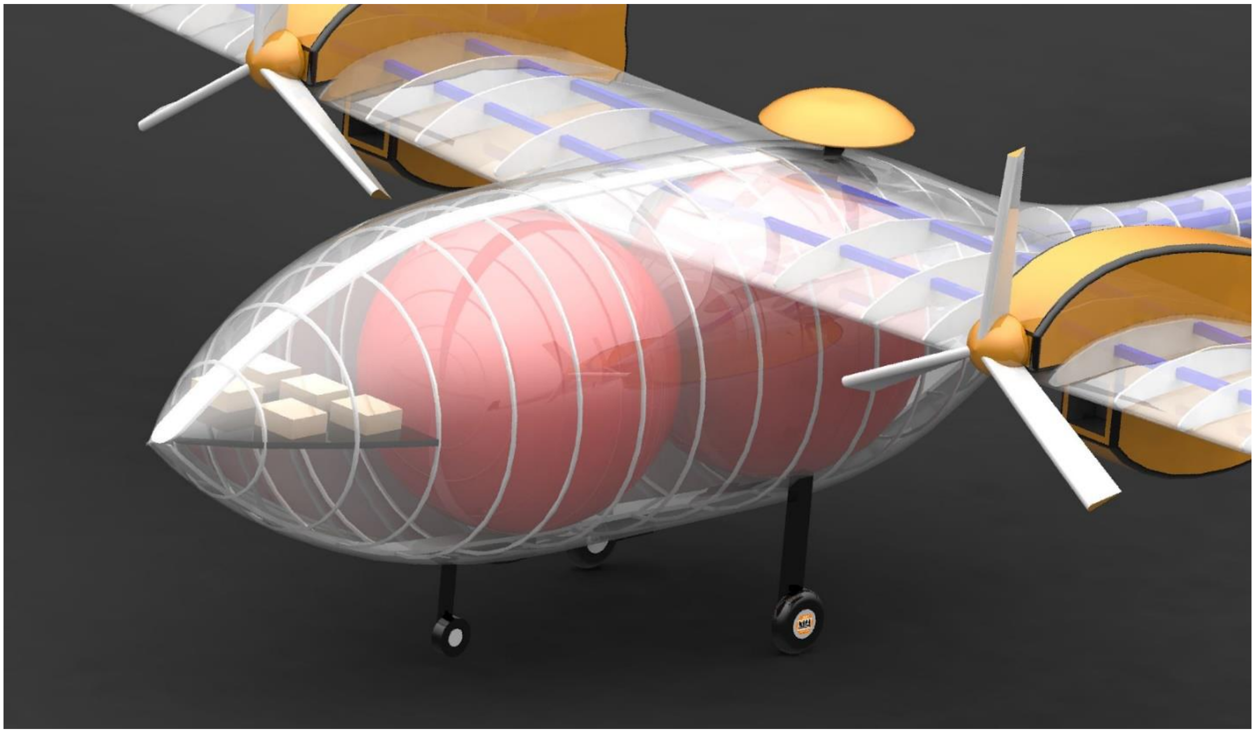


Fig 4.7: Internal view of forward fuselage

In the fuselage there are many structural components to support the plane. The first are the hoops that run the length of the fuselage, which are the grey structures in the fuselage. These hoops are made of carbon fiber and are used as a shape holding mechanism for when the aircraft fabric is stretched over the fuselage. The other component in the fuselage are the two backbones, which are the grey pieces running from the tip to the end of the taper along the top of the structure. This is made of Kevlar-reinforced carbon fiber and it is used to take on much of the aerodynamic loads that the aircraft might feel.

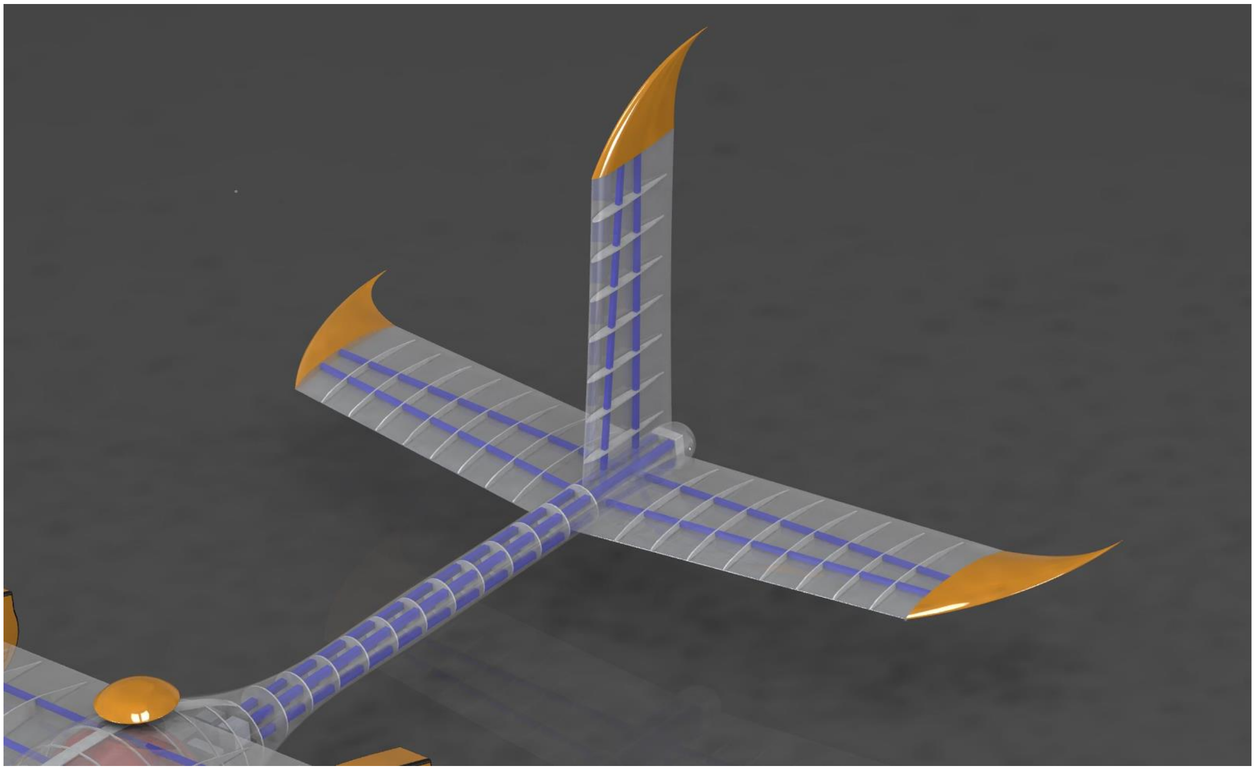


Fig. 4.8: Internal view of aft fuselage and tail structures

The last part of the plane is the thin cylindrical part of the aircraft running from the fuselage to the tail. In this section there are four carbon fiber spars, denoted as blue in this image, and discs, the grey circles in this image, that are the shape of this cylinder. The main function of the spars and discs are to help the aircraft fabric maintain shape as it goes from fuselage to tail. These also help to take on lateral and hoop stresses in flight and also take on aerodynamic loads.

Landing Gear Design and Integration

Two perspectives that should be considered when choosing landing gear are aerodynamics and mechanical design. Because the mechanical design (shock absorber, brakes, etc.) can be determined by mechanical engineers, this section will focus on keeping the aircraft stable in flight, during taxi, and when on the ground.

The following flow chart has been used to carefully select the appropriate landing gear:

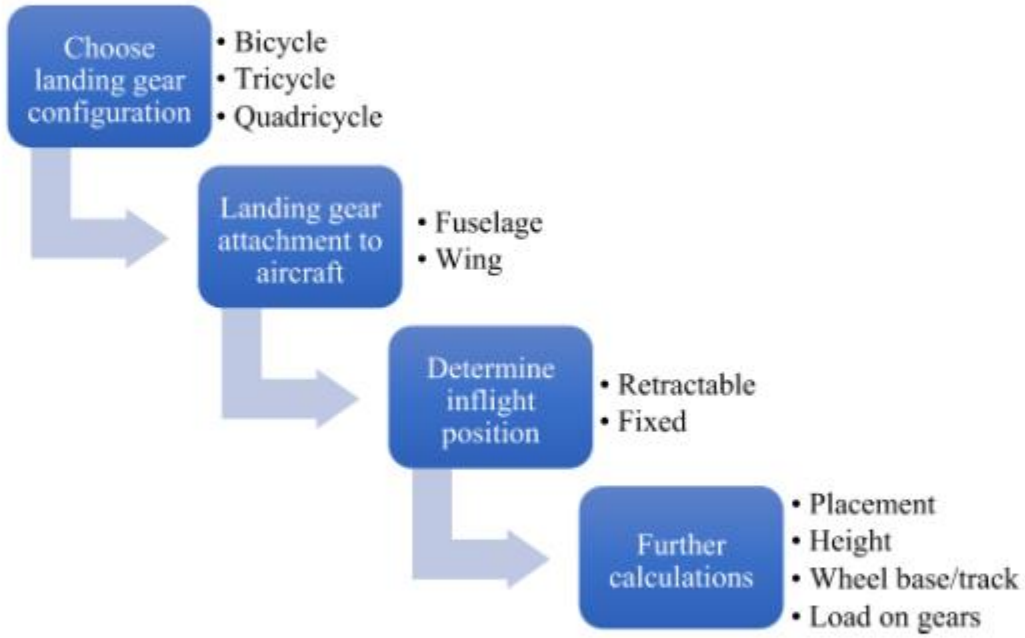


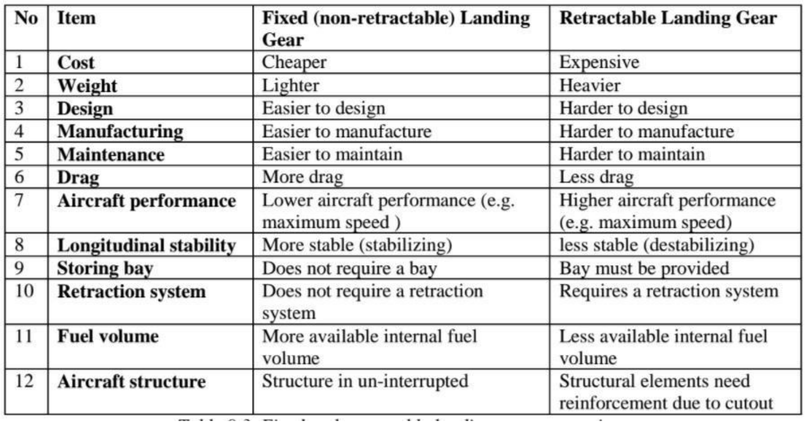
Figure 4.9: Landing gear selection process flowchart

Selecting the optimal landing gear configuration for the aircraft is the beginning step. There are multiple landing gear configurations available including, but not limited to, bicycle, tricycle, and quadricycle. For the purpose of this aircraft, the bicycle configuration was not feasible due to the *FlyP Address*' 142 foot wingspan. Having landing gear centered along the fuselage would not be a good option due to the large wingspan. The quadricycle configuration was deemed insensible for this aircraft due to the unnecessary number of wheels.

The tricycle landing gear configuration provided enough stability to the aircraft and proved less heavy than the quadricycle configuration. This design was chosen because of the large wingspan. Without wheels on each side of the fuselage, the *FlyP Address* would tip over and wing damage would occur while grounded.

The second step is to determine how the landing gear should be attached to the aircraft. The most widely used landing gear attachment choices are said to be either the fuselage or wing. For the purpose of this aircraft, the fuselage was chosen for landing gear attachment over the wing option due to the high wing configuration. Landing gear attached to a high wing configuration requires more height, weight, and is difficult to design.

The final step in landing gear configuration is choosing what the landing gear will do during flight. In flight, the landing gear can be either fixed or retractable. Deciding between using fixed or retractable landing gear is dependent upon customer preference and aircraft design. *FlyP Address*' considerations are shown in the chart below:



No	Item	Fixed (non-retractable) Landing Gear	Retractable Landing Gear
1	**Cost**	Cheaper	Expensive
2	**Weight**	Lighter	Heavier
3	**Design**	Easier to design	Harder to design
4	**Manufacturing**	Easier to manufacture	Harder to manufacture
5	**Maintenance**	Easier to maintain	Harder to maintain
6	**Drag**	More drag	Less drag
7	**Aircraft performance**	Lower aircraft performance (e.g. maximum speed)	Higher aircraft performance (e.g. maximum speed)
8	**Longitudinal stability**	More stable (stabilizing)	less stable (destabilizing)
9	**Storing bay**	Does not require a bay	Bay must be provided
10	**Retraction system**	Does not require a retraction system	Requires a retraction system
11	**Fuel volume**	More available internal fuel volume	Less available internal fuel volume
12	**Aircraft structure**	Structure in un-interrupted	Structural elements need reinforcement due to cutout

Table 4.2: Landing gear configuration comparison (Sadraey, 2012)

A retractable design is the best option for this mission. This design will limit the amount of drag added to the aircraft. While the retractable landing gear appears to be more expensive in comparison to a fixed landing gear, the weight of the *FlyP Address* wouldn't require an astronomically costly apparatus.

The landing gear consists of two main gears located behind the center of gravity that will carry approximately 85% of the total load. Each rear gear weighs 120 pounds. The front gear weighs 70 pounds and will carry roughly 15% of the load.

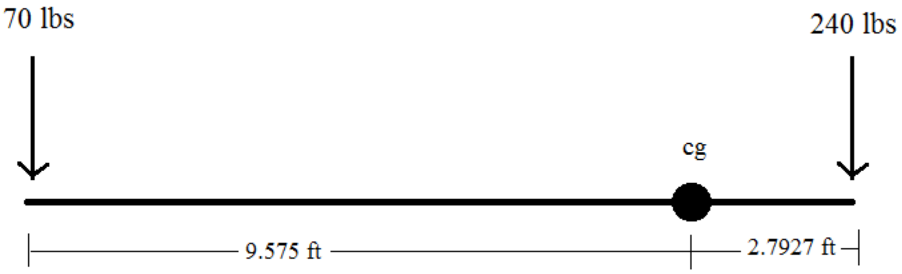


Figure 4.10: Free body diagram of landing gear

The height, wheelbase/track, and the load on gears requires extensive calculations outside of this project. For this reason, such aspects have not been included.

Systems

Component Layout and Controls Design

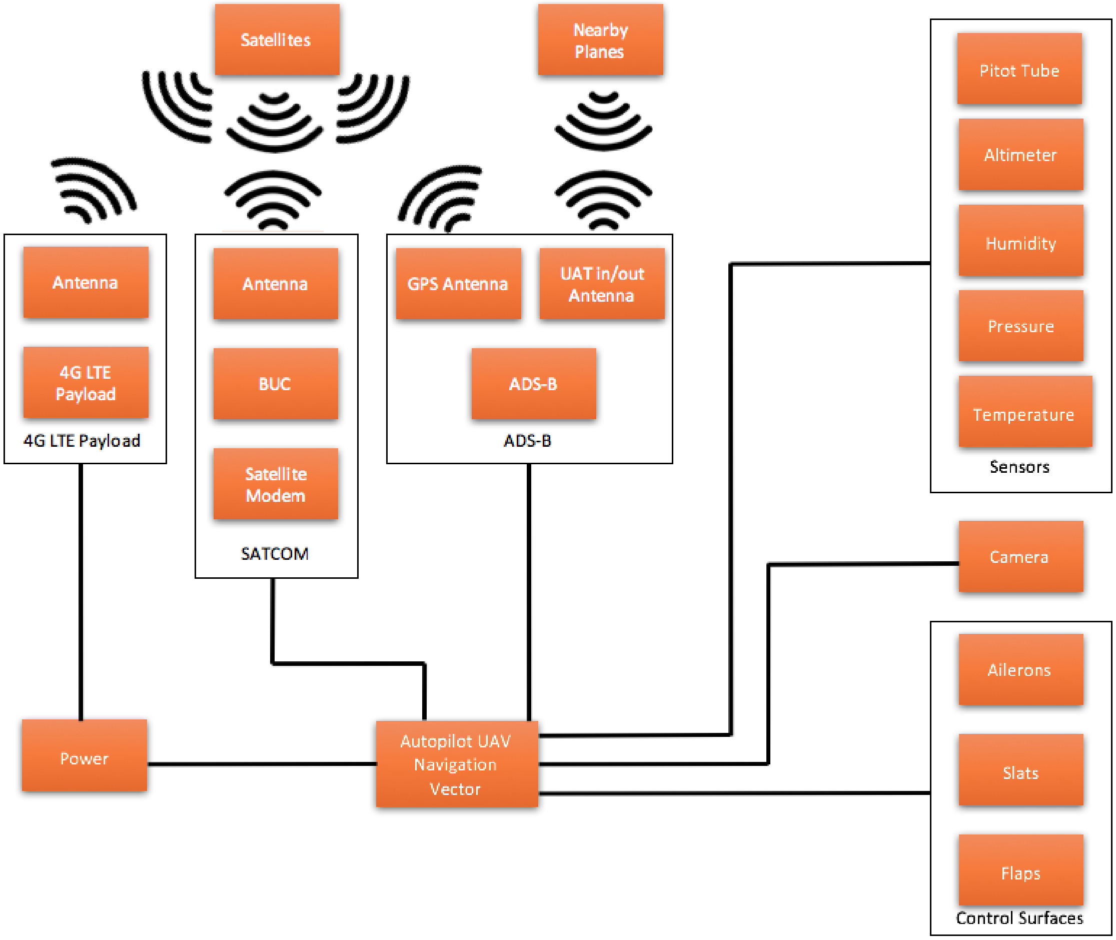


Figure 5.1: Avionics and payload connections

Payload Integration and Capability

Airspan's AIR4G telecommunications device connects to the internet service provider (ISP) via an existing satellite connection. This product was selected for *FlyP Address* because its operational range can reach the ground from 65,000 feet in altitude while providing users access to the Internet via two different mechanisms (4G LTE or 802.11x). One option is to utilize just one of the technologies, however, offering both will give the users flexibility in how they wish to connect to the Internet.

Customers will be able to utilize 4G LTE or 802.11x technologies to access the Internet from a myriad of different devices including but not limited to cell phones, tablets, laptops, etc. The 4G LTE connectivity is the current standard for high-speed mobile Internet. This will be easily accessed from mobile devices such as cell phones and tablets that are already designed to accept the 4G LTE signal. The 802.11x technology will be able to be accessed by any device that has a Wi-Fi connection available. Devices will be able to connect via any of the standards under the 802.11 family. These include the A, B, G, N, and AC standards. Each of these standards (A, B, G, N, and AC) progressively increases in speed and range, respectively. A wider range of devices will be able to connect to the 802.11x system. This range will also include smart TVs, DVD players, desktop computers, smart watches, and more.

NACA Know How opted to use five AIR4G devices in order to increase the bandwidth and user density by a factor of five.

The AIR4G requires less than 2 horsepower to run. Each unit is 1.33 x 1.15 x .508 feet. The cost of one AIR4G is approximately $10,000 depending which options are chosen. The price can climb as high as $25,000. NACA Know How estimates the cost of all five devices to be close to $78,000.

AIR4G Directional antennas enhance signal quality and range. Five antennas (one per AIR4G device) are an optimal amount to give the *FlyP Address* the nominal signal strength and quality to successfully complete its mission. More antennas can be added to increase signal strength and range if required. The AIR4G device has a capacity of four antennas per unit giving the *FlyP Address* the capability of holding up to twenty antennas. Each antenna is 2x1.667x.33 feet and weighs 4.4 pounds. Using five antennas only adds twenty-two pounds of weight to the aircraft. The antennas connect directly to the AIR4G devices which will directly provide them with power and grounding.

Avionics Overview

Unmanned Aerial Systems (UAS) are quickly outnumbering the amount of manned aircraft that take to the skies every day. As of early February 2016, there were 325,000 registered drone owners in comparison to 320,000 registered manned aircraft (Washington Post, 2016). Though the concept of a remotely piloted flying system is not new, the technologies to diminish the sizes of necessary components on board have been rapidly advancing and therefore making UAS a more reliable and applicable solution to numerous problems. Today, many airliners consist of a pilot and co-pilot even though the majority of the flight is actually controlled by an autopilot. This is obviously a safety factor when transporting hundreds of people all around the world, but for flights that need to last an entire week, having two pilots is not really an option. Therefore, a UAS such as *FlyP Address* needs to be equipped with the necessary hardware to allow a ground control station the ability to monitor the flight remotely and take control of the aircraft if the need ever arose.

Autopilot Computer

First and foremost is the autopilot computer. Computational systems that once required an entire room of hardware can now be placed in the palm of one’s hand. These systems have recently been configured with the algorithms necessary for making in-situ decisions. These decisions once required a human behind a yoke to process the situation and carry out the maneuver. Everything from autonomous take-off, flight plan execution, fly-to, hover/hold, return-to-base maneuvers when communications to the ground control station are lost and even landing can all be executed by the autopilot computer on board (UAV Navigation, 2017). For small UAVs, computers such as the 3DR Pixhawk and the DJI Naza are all that are needed to plan and execute flights. These flights can be altered and monitored from a ground control station. This is the same concept that NACA Know How wishes to execute, except on a larger scale. Since the payload will provide its own connection to satellites, data from here does not need to be passed through the UAV computer. Therefore, the only thing needed to operate *FlyP Address* would be a computer such as UAV Navigation's Vector seen below. Vector is a small rigid autopilot that can carry out all of the aforementioned capabilities from a ground control station and can be overridden and manually flown at any time. This autopilot computer will act as the "brains" of the system and connect the GPS unit, SATCOM, sensors, camera, ADS-B hardware as well as the aircraft control surfaces.

SATCOM

In order to be a fully functioning UAV, the aircraft will require onboard satellite communication technology. This will enable real time communication with the aircraft and the ability to monitor systems and control flight plans from a ground control station. BlackRay Parabolic from Gilat, seen below, is an example of the necessary SATCOM system for medium to large UAS that supports on-board intelligence. The "terminal utilizes commercial, geostationary satellite(s)" and is therefore open to commercial use since it does not require military satellite connection (Gilat, 2017). The forward and return links provide command and control capabilities as well as sensor data transfer with the ability to transmit over 20Mbps from the UAS. Figure 5.1 below shows a simulation from Delcross Technologies representing the effect of a SATCOM device similar to the BlackRay Parabolic placed in a UAV such as the

General Atomics MQ-1 Predator. The 60 cm antenna will be placed inside the UAV and constantly rotate 360 degrees to keep in constant communication with the passing satellites. It will then be connected to the BOC module, the modem, and then to the autopilot computer.

ADS-B

Automatic Dependent Surveillance-Broadcast (ADS-B) is necessary for all aircraft beginning January 1st, 2020 (FAA, 2017). This technology allows all aircraft in the area to recognize one another. With the nature of UAVs, detect and avoidance along with ADS-B requirements have been fundamental in the discussions about full integration of unmonitored and autonomous aircraft. Since the *FlyP Address* will be operating as a UAV that will perform automated take-off, ascent, cruise, descent and landing maneuvers, it is paramount that the aircraft is equipped with appropriate technology. From uAvionix the echoUAT is a transceiver seen in Figure 5.2 that incorporates a dual-link 1090/978 ADS-B receiver with a 978 MHz B1S UAT transmitter. The echoUAT is a small and compact ADS-B in and out system that was chosen due to its lightweight and compact form while also meeting the requirements of TSO-154c Class B1S. Another advantage to the echoUAT is that it has a GPS built in and receives NEMA sentences that can be used by the autopilot computer. The autopilot computer will connect directly to the echoUAT and transmit its location to surrounding aircraft as well as receive information about the location, direction and relative velocity of those aircraft so that the autopilot can detect and avoid these aircraft if need be.

Camera

As a precautionary measure, a camera will be placed on board *FlyP Address* so that personnel at the ground control station can have visual if they need to take over control of the aircraft and fly it back to safety. The CM160 from UAV Vision, shown below, is a standard multi-sensor camera that will more than cover the necessities of the *FlyP Address*. With a weight of just around 3 pounds, length of 9 inches, power consumption of 12W and High Definition digital video output, this camera has a small SWaP for the combination of video output and sensor capabilities such as object tracking (UAVVision, 2017).

Performance Estimates

Aircraft Configuration

The component layout plays a very significant role in designing an aircraft. To locate and find the aircraft's center of gravity, the components had to be strategically placed. There is little flexibility in laying out all components because too much weight in one location of the aircraft not accounted for could be catastrophic.

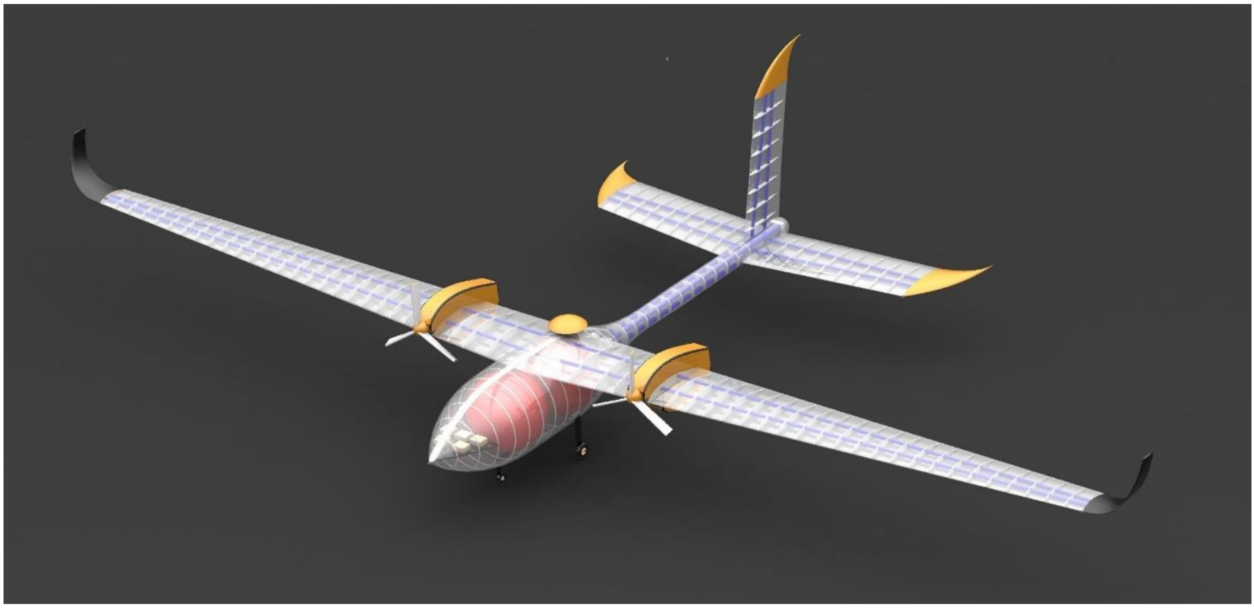


Figure 6.1: Internal component view with wing spars, fuel tanks, and payload

As shown in Figure 6.1, the components range from things as simple and small as batteries and computers to motors and fuel tanks. Knowing the fuel cells are the heaviest component, that is where the positioning started. The front of the two fuel tanks was placed seven feet from the front tip of the fuselage as shown in Figure 6.2 below. Placing them too far forward as well as too far back could result in trouble for stability.

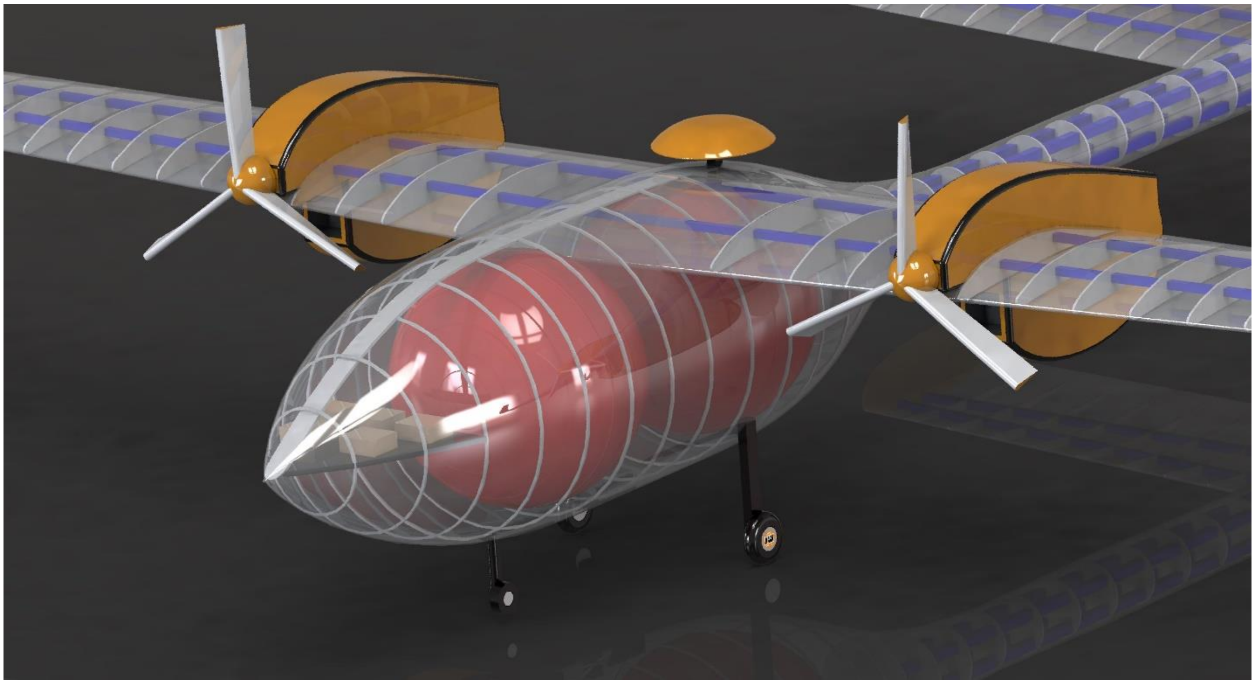


Figure 6.2: Internal component view of fuselage containing fuel tanks and payload

Another set of components that are important pieces to position are the motors. Wanting the motors to be in the wings minimized the various locations for them. As shown in Figure 6.3 below, the motors were placed close to the fuselage and to the root of the wing, fourteen feet from the front tip of the fuselage. This was chosen because of the sturdiness of the root airfoil as opposed to the thinner and more aerodynamic airfoils further out in the wing.

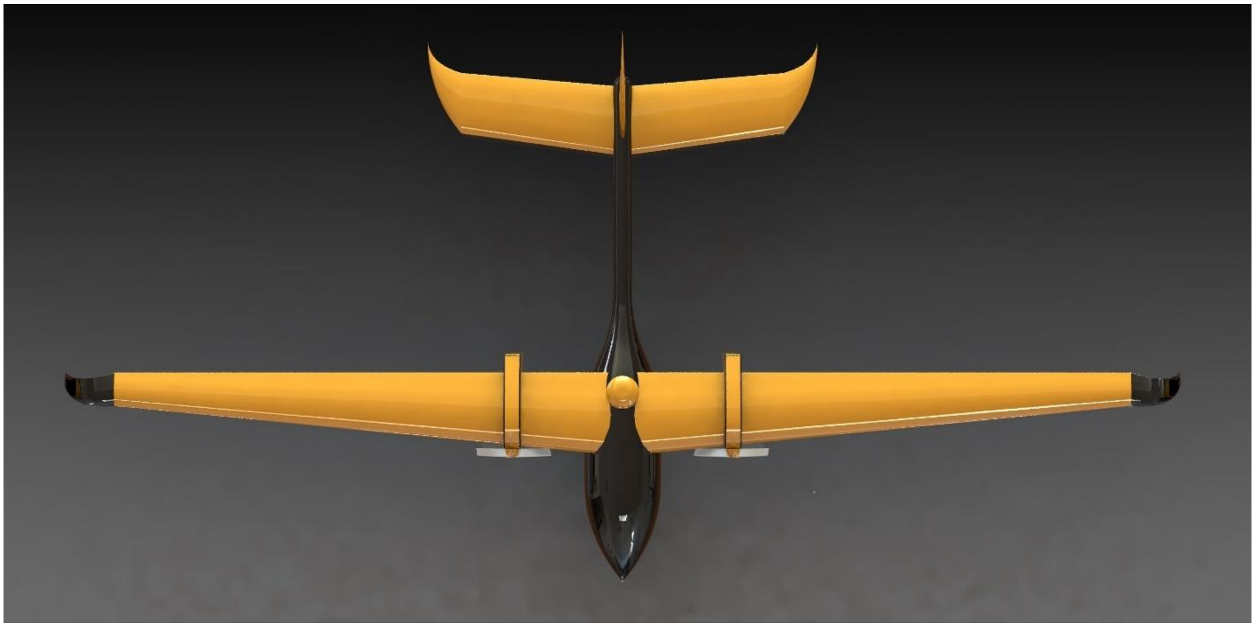
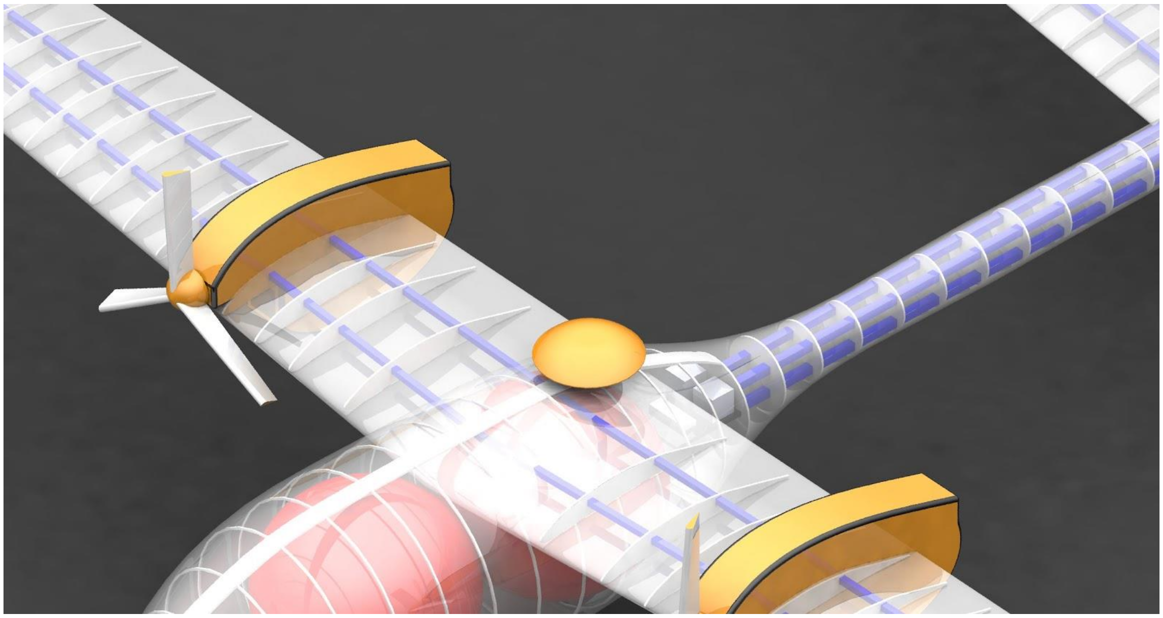


Figure 6.3: Overhead configuration displays tail sizing with respect to wing size

Once all the heavier components were positioned, the rest were not as crucial. The decision was made for the batteries, NAV sensors and flight computer to be in the same general location. All these components range from twenty-six feet to twenty-eight feet from the front tip of the aircraft. There is a shelf at the rear of the fuselage designed to tuck these components into optimal position.



The payload changed throughout the design process, therefore it was one of the last of this round of components to be positioned. Once the final weight and dimensions were known, it was added to the aircraft. Refer to Figure 6.2 to see that the payload is nested into the front tip of the aircraft. The payload is mounted to a shelf and is located three feet from the front tip.

Tail Volumes

The tail sizing of *FlyP Address*' tail was dimensionalized to have the following parameters:

$$y_{VT} = y_{HT} = 34.3 \text{ ft. (Distance from } C_G\text{)}$$

$$S_{HT} = 300 \text{ ft}^2$$

$$S_{VT} = 105 \text{ ft}^2$$

Using these parameters, the aerodynamics team was able to calculate the tail volume coefficients to be the following:

$$V_{HT} = (S_{HT} \cdot y_{HT})/(S \cdot c_{avg}) = 1.1681$$

$$V_{VT} = (S_{VT} \cdot y_{VT})/(S \cdot b) = 0.0279$$

Initial stability calculations show that this may not be the most stable design, therefore it is a goal of NACA Know How's to improve the static margin for the final design.

Best Speeds

Based upon the equations given in Dr. Jacob's performance lecture slides, the best speeds for both max range and max endurance, for prop driven aircraft, can be directly calculated. For the maximum endurance, the required velocity is given by:

$$V_{C_L^{3/2}/C_D|_{\max}} = \sqrt{\frac{2}{\rho}\sqrt{\frac{1}{3\pi eARC_{Do}}}\frac{W}{S}}$$

While the velocity for maximum range is given by:

$$V_{L/D_{\max}} = \sqrt{\frac{2}{\rho}\sqrt{\frac{1}{\pi eARC_{Do}}}\frac{W}{S}}$$

Using the parameters for *FlyP Address* and an e value of .9 the best speeds are obtained and shown below:

$$V_{\text{Max Endurance}} = 203.3536 \text{ ft/s}$$

$$V_{\text{Max Range}} = 267.628 \text{ ft/s}$$

Note that S_{Eff} was used in the calculations to simulate the winglets.

Range and Endurance

To calculate the range and endurance for *FlyP Address*, the spreadsheet below is used. At 60,000 feet, the estimated flight time is at 320 hours or 13.3 days with a range of 100,000 nautical miles. The plots show the different flight endurances and ranges for different weights of payload. The amount of payload that *FlyP Address* is carrying has a significant effect on its range and endurance. At max payload, the range will decrease by around 5000 nautical miles and endurance by 20 hours. This means that when preparing the mission for *FlyP Address* the payload weight must be taken accounted for when determine how long the plane will fly.

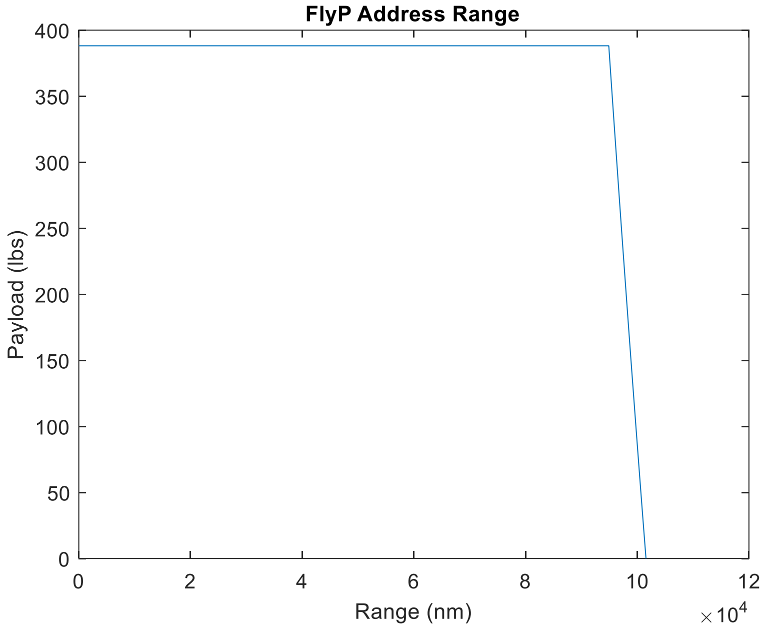


Figure 6.4: Plot of FlyP Address range

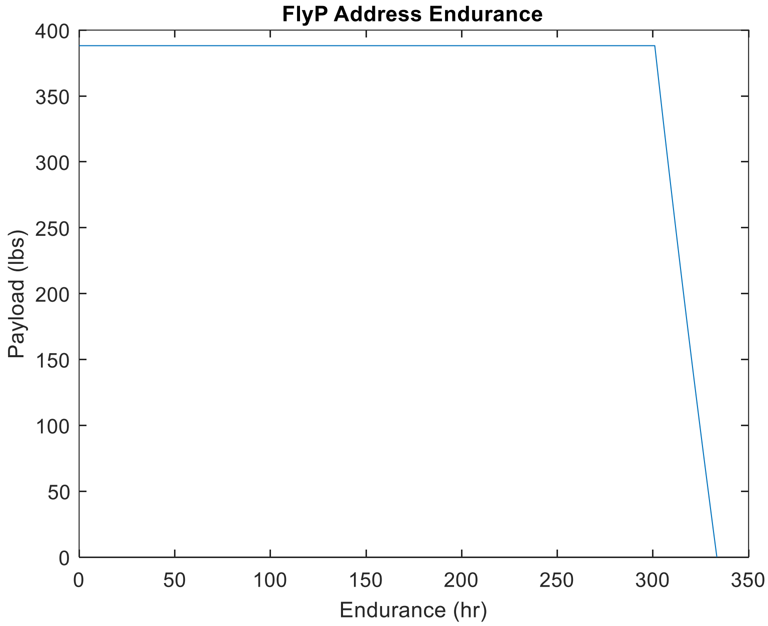


Figure 6.5: Plot of FlyP Address endurance

Mission Analysis

When *FlyP Address* takes off fully loaded in fuel, it will climb to 60,000 feet and establish itself at cruise altitude travelling to the desired location as determined by ground control. Upon arrival, it circles the intended area for maintaining internet provision while holding altitude. With an endurance just under two weeks, it can provide internet that entire time if the takeoff location is nearby, or it can provide internet for a shorter duration but to a remote location. Due to its autonomy, little interaction, support, or override is necessary from ground control should the mission profile remain constant throughout. Depending on demand, when *FlyP Address* has exhausted its fuel, the location of interest can be promptly covered by a duplicate fully-fueled aircraft while the first returns and lands for refueling and maintenance.

Productivity Comparison

FlyP Address' main mission is to fly at 60,000 feet for over a week and provide Wi-Fi to various places around the world. The competitors with the most similar mission parameters are the Zephyr 8, the Facebook Aquila, and the Boeing Phantom Eye.

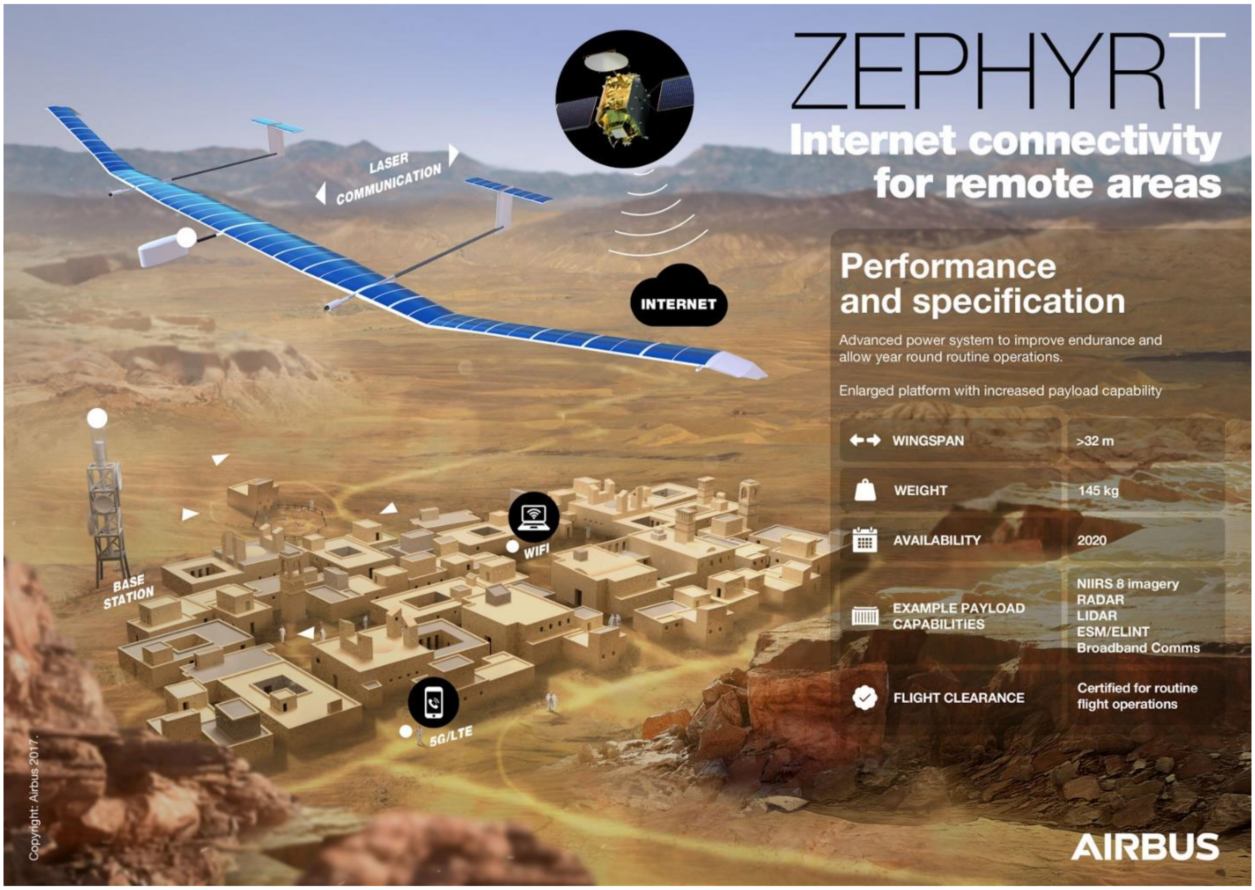
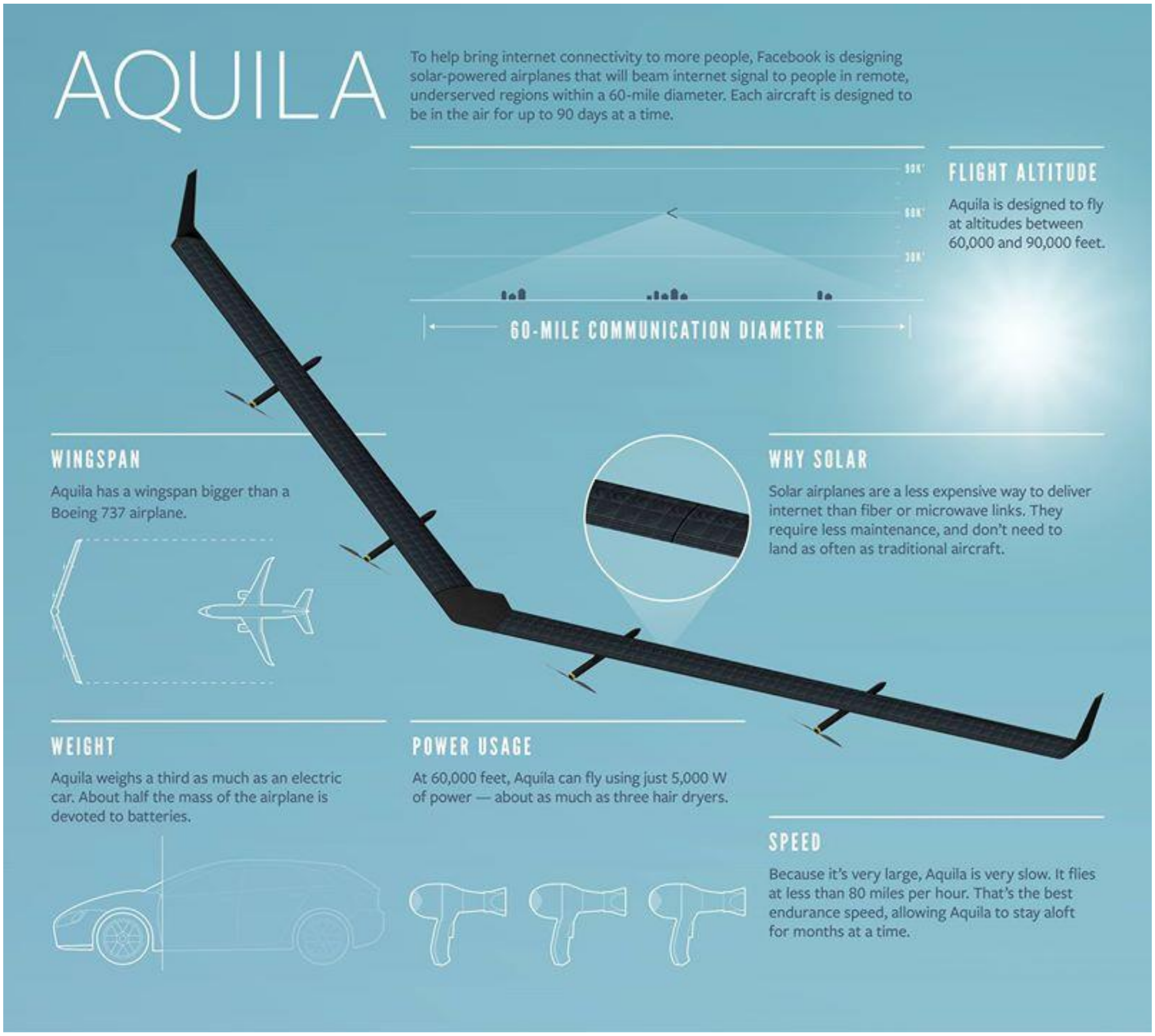


Figure 6.6: Zephyr infographic (Zephyr T, 2014)

The Zephyr 8's mission was to be a pseudo-satellite flying at 65,000 feet and provide Wi-Fi all across the world. The Zephyr uses solar panels and was only scheduled to work during the months which provide to most sunlight to the United States. The Zephyr also carries a five kilogram payload of communications and surveillance gear. Though it flew for fourteen days non-stop, this aircraft failed to sell because it cannot complete its mission without having constant exposure to sunlight. This cannot compete with *FlyP Address* because *FlyP Address* can carry out Wi-Fi to all places around the world without need of being in a place of constant sunlight for the solar panels.



To help bring internet connectivity to more people, Facebook is designing solar-powered airplanes that will beam internet signal to people in remote, underserved regions within a 60-mile diameter. Each aircraft is designed to be in the air for up to 90 days at a time.

FLIGHT ALTITUDE

Aquila is designed to fly at altitudes between 60,000 and 90,000 feet.

WINGSPAN

Aquila has a wingspan bigger than a Boeing 737 airplane.

WHY SOLAR

Solar airplanes are a less expensive way to deliver internet than fiber or microwave links. They require less maintenance, and don't need to land as often as traditional aircraft.

WEIGHT

Aquila weighs a third as much as an electric car. About half the mass of the airplane is devoted to batteries.

POWER USAGE

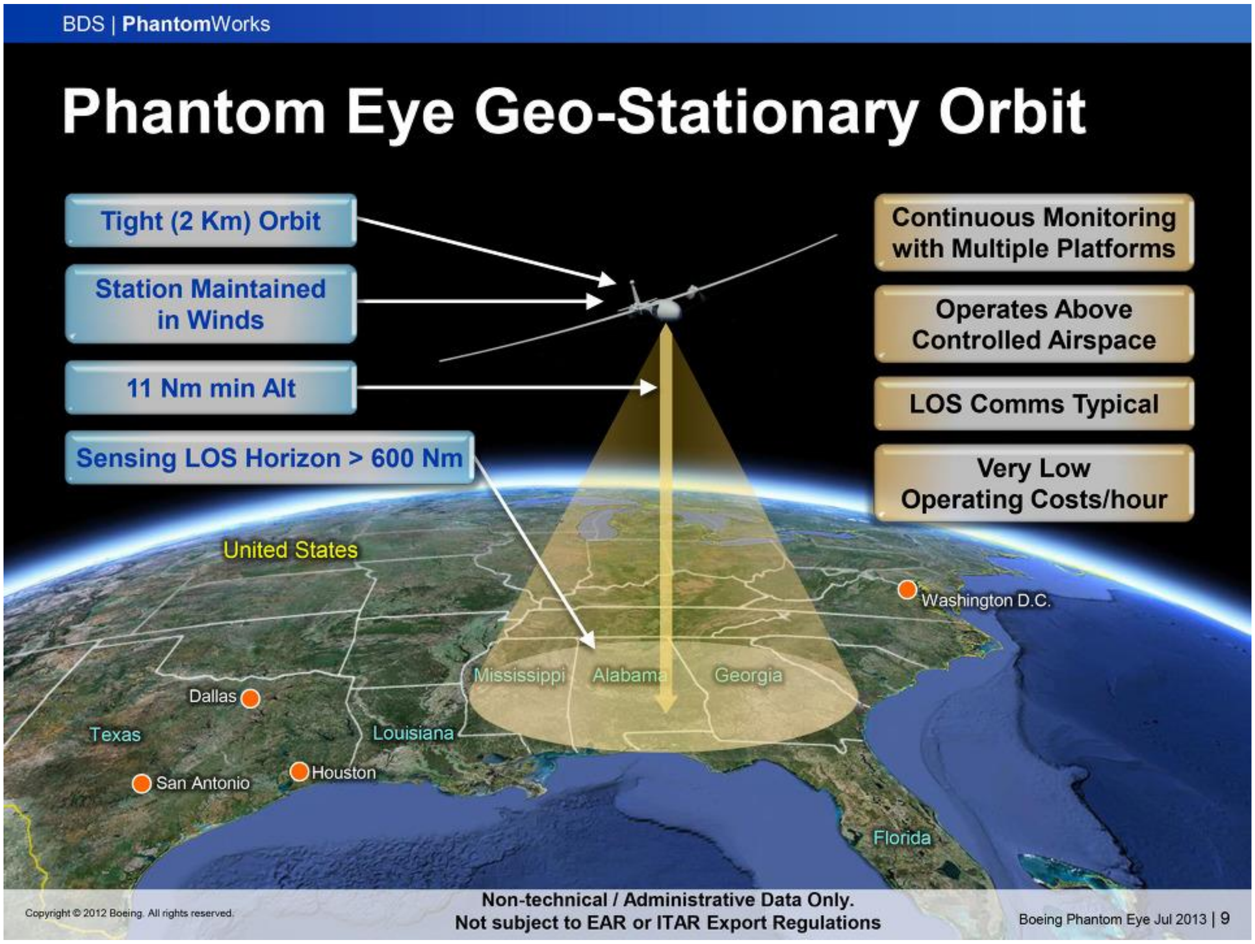
At 60,000 feet, Aquila can fly using just 5,000 W of power — about as much as three hair dryers.

SPEED

Because it's very large, Aquila is very slow. It flies at less than 80 miles per hour. That's the best endurance speed, allowing Aquila to stay aloft for months at a time.

Figure 6.7: Aquila infographic (Aquila, 2016)

The Facebook Aquila's mission was to fly at 60,000 feet and deliver Wi-Fi to a sixty mile radius around the world. The Aquila had the closest mission parameters to *FlyP Address*' mission. The Aquila was completely covered in solar panels and can only fly in places where sunlight is available at all hours, an issue NACA Know How has already found a solution to. A big issue with the Facebook Aquila was the takeoff and landing gear and parameters used. The takeoff had to be assisted by a cart, meaning all airports would need to have this gear with them for the Aquila to takeoff. This is not an issue for *FlyP Address* because it has the necessary landing gear to land on its own and it also has the ability to takeoff by itself without the need for any extra hardware.



BDS | **Phantom**Works

Phantom Eye Geo-Stationary Orbit

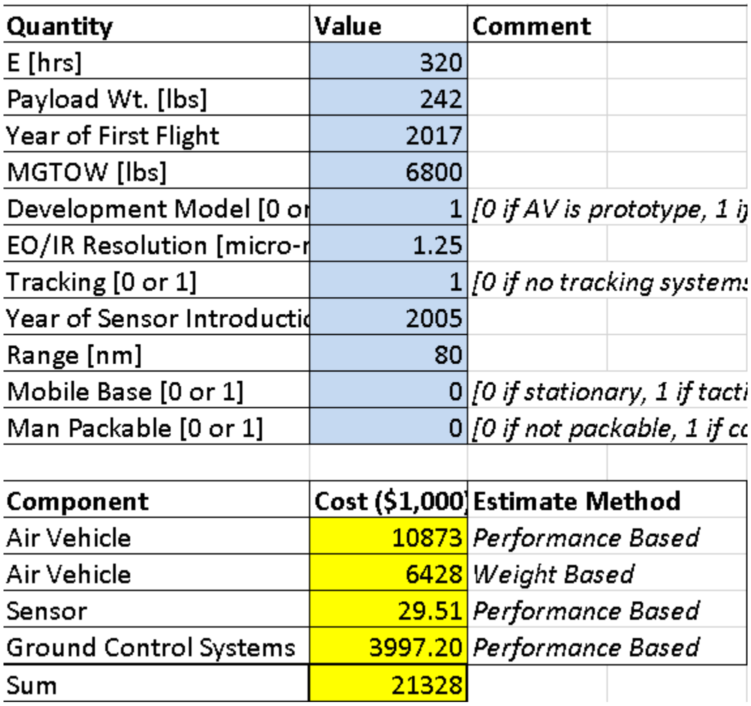
- Tight (2 Km) Orbit
- Station Maintained in Winds
- 11 Nm min Alt
- Sensing LOS Horizon > 600 Nm

- Continuous Monitoring with Multiple Platforms
- Operates Above Controlled Airspace
- LOS Comms Typical
- Very Low Operating Costs/hour

Non-technical / Administrative Data Only.
Not subject to EAR or ITAR Export Regulations

Boeing Phantom Eye Jul 2013 | 9

Figure 6.8: Phantom Eye infographic (Phantom Eye, 2012)



Quantity	Value	Comment	
E [hrs]	320		
Payload Wt. [lbs]	242		
Year of First Flight	2017		
MGTOW [lbs]	6800		
Development Model [0 or	1	*[0 if AV is prototype, 1 i*	
EO/IR Resolution [micro-r	1.25		
Tracking [0 or 1]	1	*[0 if no tracking system*	
Year of Sensor Introducti	2005		
Range [nm]	80		
Mobile Base [0 or 1]	0	*[0 if stationary, 1 if tacti*	
Man Packable [0 or 1]	0	*[0 if not packable, 1 if c*	

Component	Cost ($1,000	Estimate Method
Air Vehicle	10873	*Performance Based*
Air Vehicle	6428	*Weight Based*
Sensor	29.51	*Performance Based*
Ground Control Systems	3997.20	*Performance Based*
Sum	21328	

Spreadsheet 6.1

The last plane that has a similar mission is the Boeing Phantom Eye. Its mission parameters were to fly at 65,000 feet and carry communications and surveillance payload for military defense purposes. This plane can fly between seven and ten days non-stop and runs on hydrogen. This plane can achieve all the parameters that Fly P Address can, but has been dismissed because of its extreme cost. Its high cost is mainly due to the communications gear aboard the aircraft. The cost of the aircraft is $55 million. *FlyP Address* can fly non-stop for thirteen days, which three more days than the Phantom Eye. Also, as seen above, *FlyP Address* will only cost $21.3 million with its Wi-Fi payload on board, which is much less than the Phantom Eye and will attract far more customers than the competition.

These different planes, which all have similar mission parameters to that of *FlyP Address*, have failed in various ways and through these ways NACA Know How has learned and have found various solutions to make *FlyP Address* fit all the mission parameters.

Table of Major Performance Parameters

V_{max} at 60000 feet	436 ft/sec
V_{stall} at 60000 feet	99.12 ft/sec
V best range at 60000 feet	267.63 ft/sec
V best endurance at 60000 feet	203.4 ft/sec
Range	100000 nm
Endurance	320 hours
R/C	19.7 ft/sec
Time to Climb	51 minutes
Fuel to Climb	10 pounds
Time to Descend	23.47 hours
Sink Rate	.71 ft/sec
Ceiling	62,490 feet
Turn Rate	20.63 degrees/sec
Turn Radius	277.77 feet
Take-Off Distance	1,611 feet

Landing Distance	1,563 feet
L/D max	165.9887
Cl	.918
Cd	.0372
V_{cruise} at 60000 feet	100 ft/sec

Table 7.1: Table of Major Performance Parameters

Performance Analysis Plots

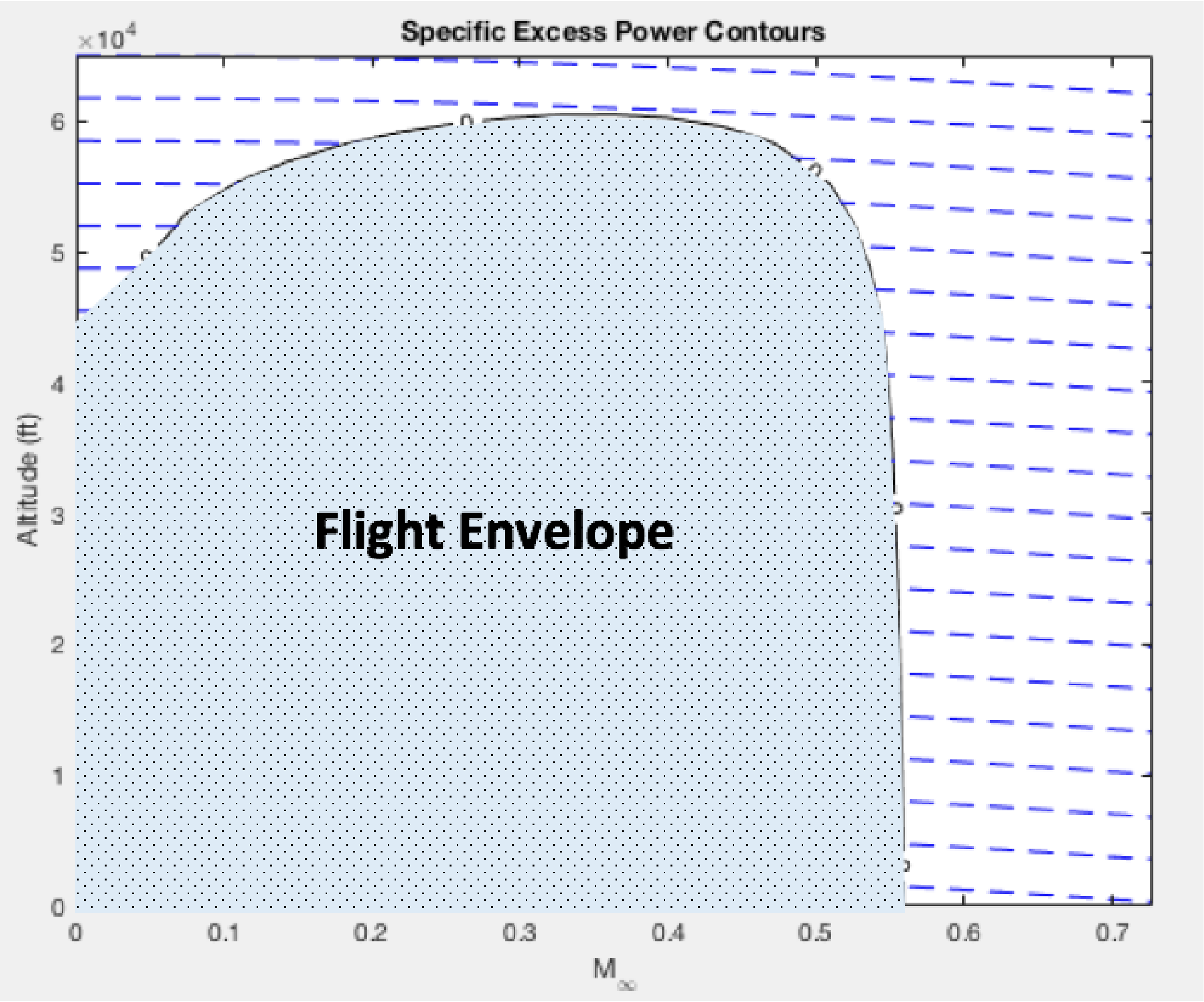


Figure 8.1: Flight Envelope

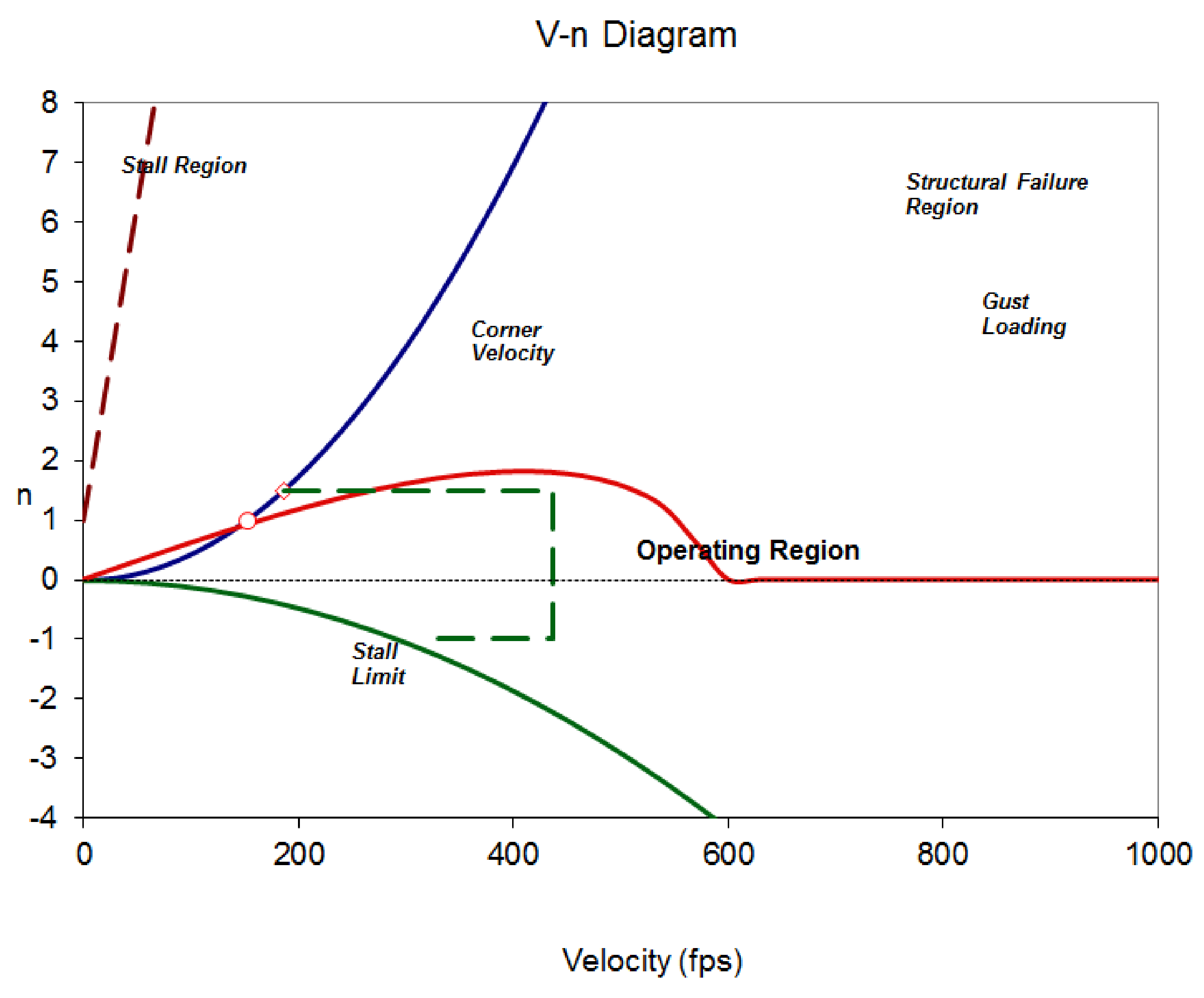


Figure 8.2: V-n Diagram for operating velocities

Take Off

Using 5° flaps, tire area of 2.5 square feet, coefficient of friction of the pavement at 0.05, seven hundred pounds of lift, and thirty-five feet of "climb over obstacle" gives *FlyP Address* a takeoff distance of approximately 1000 feet. The nose of the aircraft begins to climb for 182 feet after the takeoff distance and then transitions for an additional sixty-six feet. To achieve the needed "climb over obstacle" of 35 feet, a distance of 367 feet is required. This makes the total takeoff distance 1611 feet. All of this can be seen in the below figure and graph.

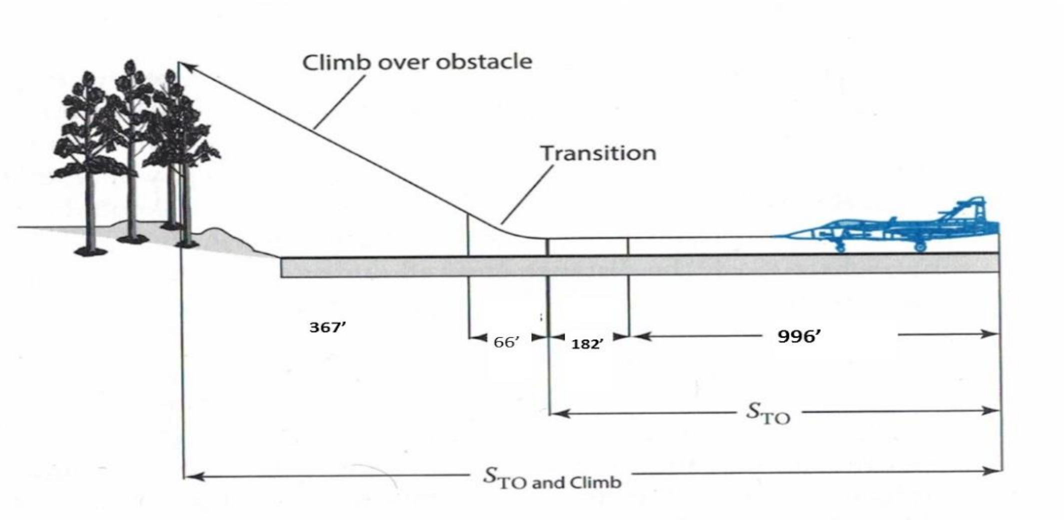


Figure 8.3: Takeoff schematic

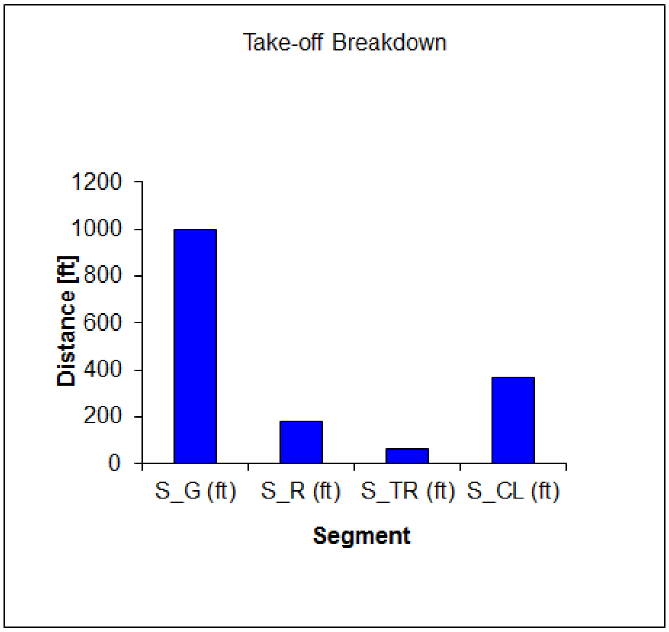


Figure 8.4: Takeoff distance

Landing

To achieve a landing over the 35 feet "land over obstacle", a distance of 624 feet is necessary. The transition takes place over an interval of 88 feet. At this point the front landing gear touches down. After a period of 271 feet the aircraft is completely grounded and the brakes are engaged. The aircraft will slow down prior to coming to a halt over a span of 580 feet making the total landing distance 1563 feet.

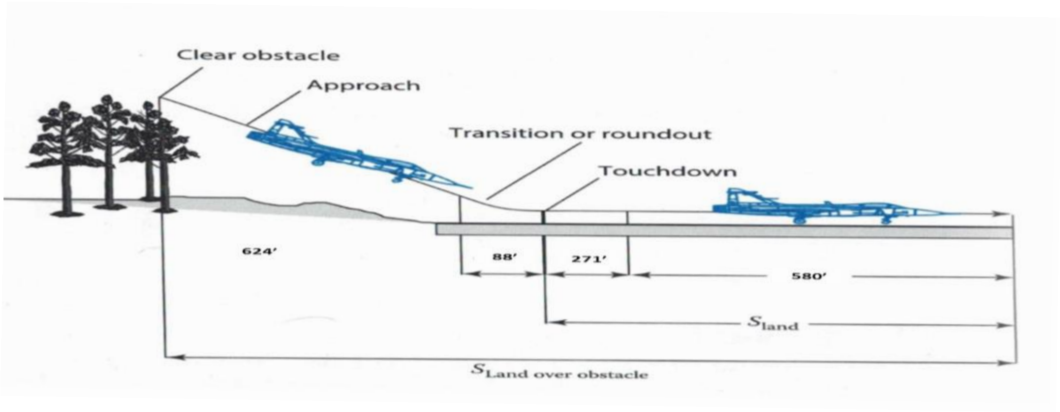


Figure 8.5: Landing schematic

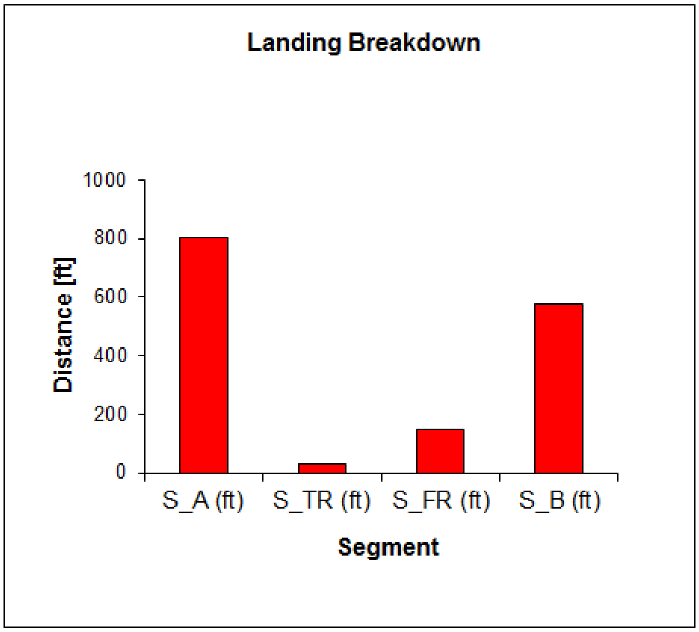
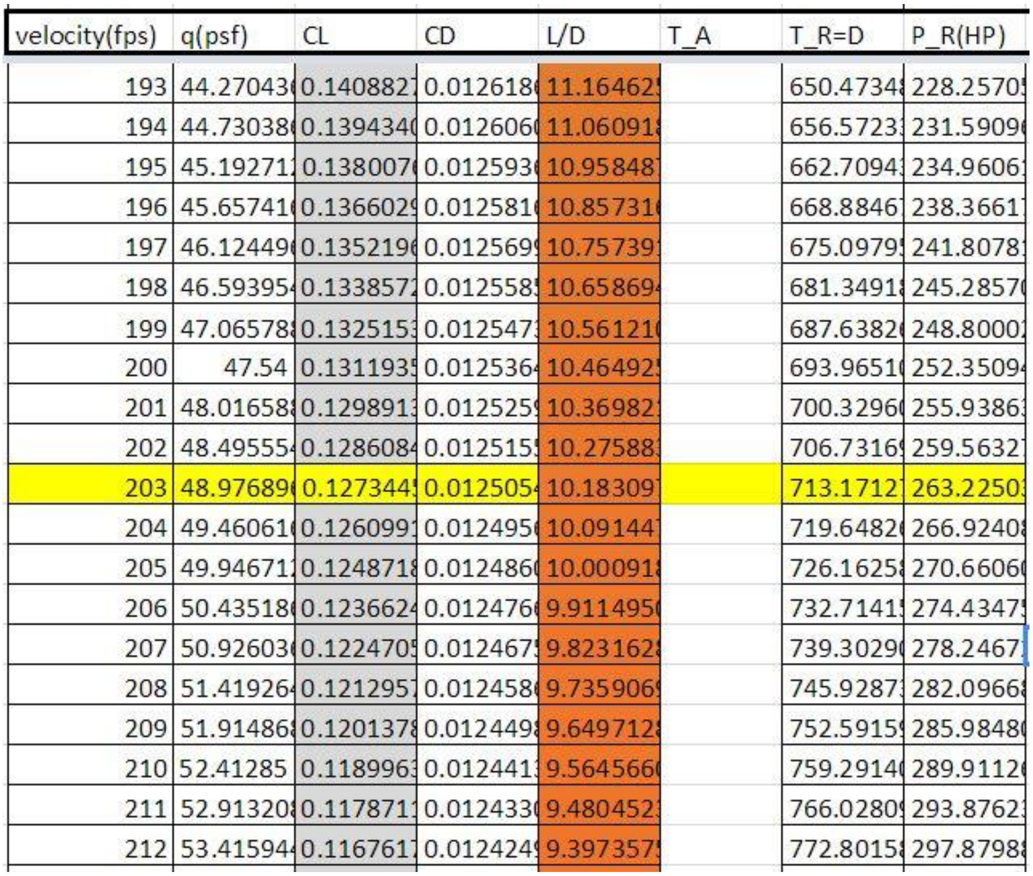


Figure 8.6: Landing distance

Excess Power

The *FlyP Address* has three hundred horsepower available yet requires only fifty horsepower. The power required was calculated using $P = T_R V_R$ and the plane configuration Excel spreadsheet can be seen below.



velocity(fps)	q(psf)	CL	CD	L/D	T_A	T_R=D	P_R(HP)
193	44.27043	0.140882	0.012618	11.16462		650.4734	228.2570
194	44.73038	0.139434	0.012606	11.06091		656.5723	231.5909
195	45.19271	0.138007	0.012593	10.95848		662.7094	234.9606
196	45.65741	0.136602	0.012581	10.85731		668.8846	238.3661
197	46.12449	0.135219	0.012569	10.75739		675.0979	241.8078
198	46.59395	0.133857	0.012558	10.65869		681.3491	245.2857
199	47.06578	0.132515	0.012547	10.56121		687.6382	248.8000
200	47.54	0.131193	0.012536	10.46492		693.9651	252.3509
201	48.01658	0.129891	0.012525	10.36982		700.3296	255.9386
202	48.49555	0.128608	0.012515	10.27588		706.7316	259.5632
203	48.97689	0.127344	0.012505	10.18309		713.1712	263.2250
204	49.46061	0.126099	0.012495	10.09144		719.6482	266.9240
205	49.94671	0.124871	0.012486	10.00091		726.1625	270.6606
206	50.43518	0.123662	0.012476	9.911495		732.7141	274.4347
207	50.92603	0.122470	0.012467	9.823162		739.3029	278.2467
208	51.41926	0.121295	0.012458	9.735906		745.9287	282.0966
209	51.91486	0.120137	0.012449	9.649712		752.5915	285.9848
210	52.41285	0.118996	0.012441	9.564566		759.2914	289.9112
211	52.91320	0.117871	0.012433	9.480452		766.0280	293.8762
212	53.41594	0.116761	0.012424	9.397357		772.8015	297.8798

Spreadsheet 8.1: Lift and drag coefficients for cruise velocity

The area highlighted in yellow is representative of the data corresponding to the *FlyP Address*' cruising velocity of 203 feet per second. Having 37 extra horsepower, there is no lack in available energy needed to fly the *FlyP Address*. This excess power can be utilized to climb the necessary 60,000 feet in altitude.

As seen in the excess power plots and other calculations there is plenty of excess power throughout the entire climb and at cruise. This helps when at cruise to throttle back which conserves fuel and allows the longer flight times required for *FlyP Address*'s mission.

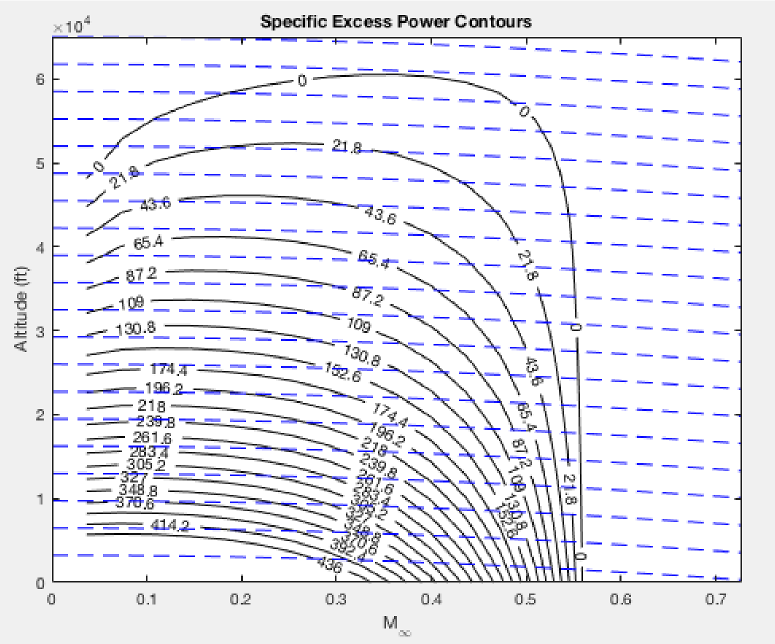


Figure 8.7: Specific Power Plot

Time and Fuel to Climb

For calculating the max rate of climb the following equation was used:

$$R/C_{l_{max}} = \frac{\eta_{pr}P}{W} - \left[\frac{2}{\rho}\sqrt{\frac{K}{3C_{D0}}}\frac{W}{S}\right]^{\frac{1}{2}} \frac{1.155}{(L/D)_{max}}$$

With the known performance parameters, a max rate of climb at altitude is 19.7 feet per second. This number increases as there is a decrease in altitude but for this case it only reduces by about one foot per second. Once the max rate of climb is known divide the target altitude by the R/C_{lmax} to get that it takes 3050 seconds or fifty-one minutes to climb 60,000 feet. For the fuel to climb, the engines burn at a specific fuel consumption rate. For *FlyP Address* the engines use 0.04 pound per horsepower-hour of hydrogen fuel. Given this and the time to climb the fuel estimate to achieve altitude is 10 pounds of fuel.

Weights

Final Component Weight Breakdown

The breakdown of weight in *FlyP Address* is shown in the figure below. All structural component weights were calculated by approximation using rectangular prisms, cylinders, and tubes. These were best fit to average values of length, width, and height of each component and the resulting volumes were multiplied by material densities to provide an idea of the final weight. In cases of more ambiguous calculations such as estimating volume of a rib with a rectangle, an attempt was made to slightly overestimate the weight to ensure unaccounted for materials didn't ground the plane. The total weight for structural components comes out to be 2433.73 pounds.

For non-structural components such as engines, weight values were retrieved from manufacturer specifications found online. Additional fudge weights were also included to account for random piping, pumps, regulators, and insulation which will need to be incorporated by lowly mechanical engineers that aren't cool enough to design an actual plane like the experts at NACA Know How are. The total weight for non-structural components comes out to be 4828.55 pounds. This number also includes a 220-pound payload weight.

Component Weight Breakdown

Item #	Component	Quantity	Total Weight of all Components (lbs)
1	Main Wing Spars (CFRP)	4	374.22
2	Main Wing Ribs (CFRP)	90	546.15
3	Main Wing Skin (Aircraft Fabric)	1	74.63
4	Tail Spars (CFRP)	2	78.44

5	Tail Ribs (CFRP)	30	46.74
6	Tail Skin (Aircraft Fabric)	1	36.92
7	Vertical Stabilizer Spars (CFRP)	2	34.76
8	Vertical Stabilizer Ribs (CFRP)	12	17.27
9	Vertical Stabilizer Skin (Aircraft Fabric)	1	10.12
10	Front Fuselage Spine (CFRP)	2	84.67
11	Front Fuselage Spine (Kevlar)	2	301.60
12	Rear Fuselage Spars (CFRP)	4	50.66
13	Front Fuselage Ribs (CFRP)	20	251.96
14	Rear Fuselage Ribs (CFRP)	20	76.64
15	Front Fuselage Skin (Aircraft Fabric)	1	145.01
16	Rear Fuselage Skin (Aircraft Fabric)	1	43.95
17	Wing Mounting Assembly	1	140.00
18	Tail Mounting Assembly	1	120.00
19	2.3L H2 Engines	2	1168.00
20	Spherical H2 Tanks	2	719.55
21	Liquid H2 (Fuel)	1	2111.00
22	Misc Weight (Pipes, Insulation, Regulators, etc)	1	200.00
23	Front Landing Gear	1	70.00
24	Rear Landing Gear	2	240.00
25	Automated Flight System (with backup inflatable autopilot)	1	75.00
26	Payload	1	220.00
27	Batteries	1	25
TOTALS			7262.28

Table 9.1: Major component weight breakdown

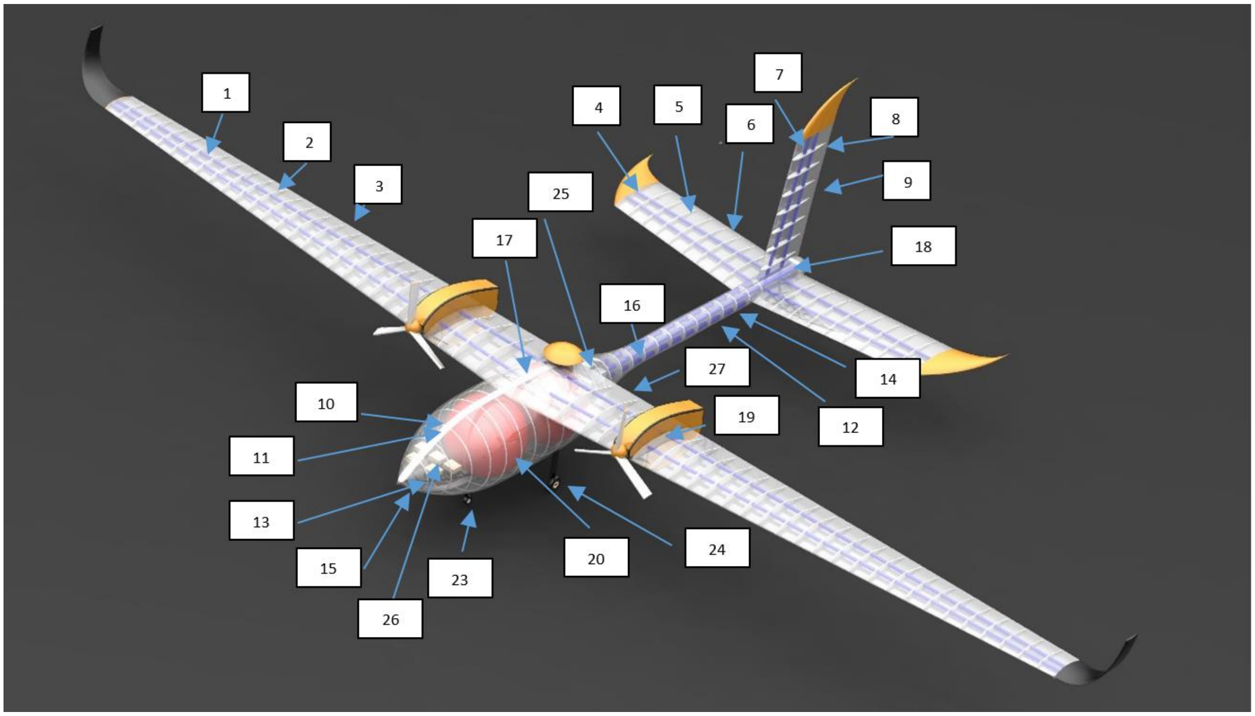


Figure 9.1: Internal view with labeled components

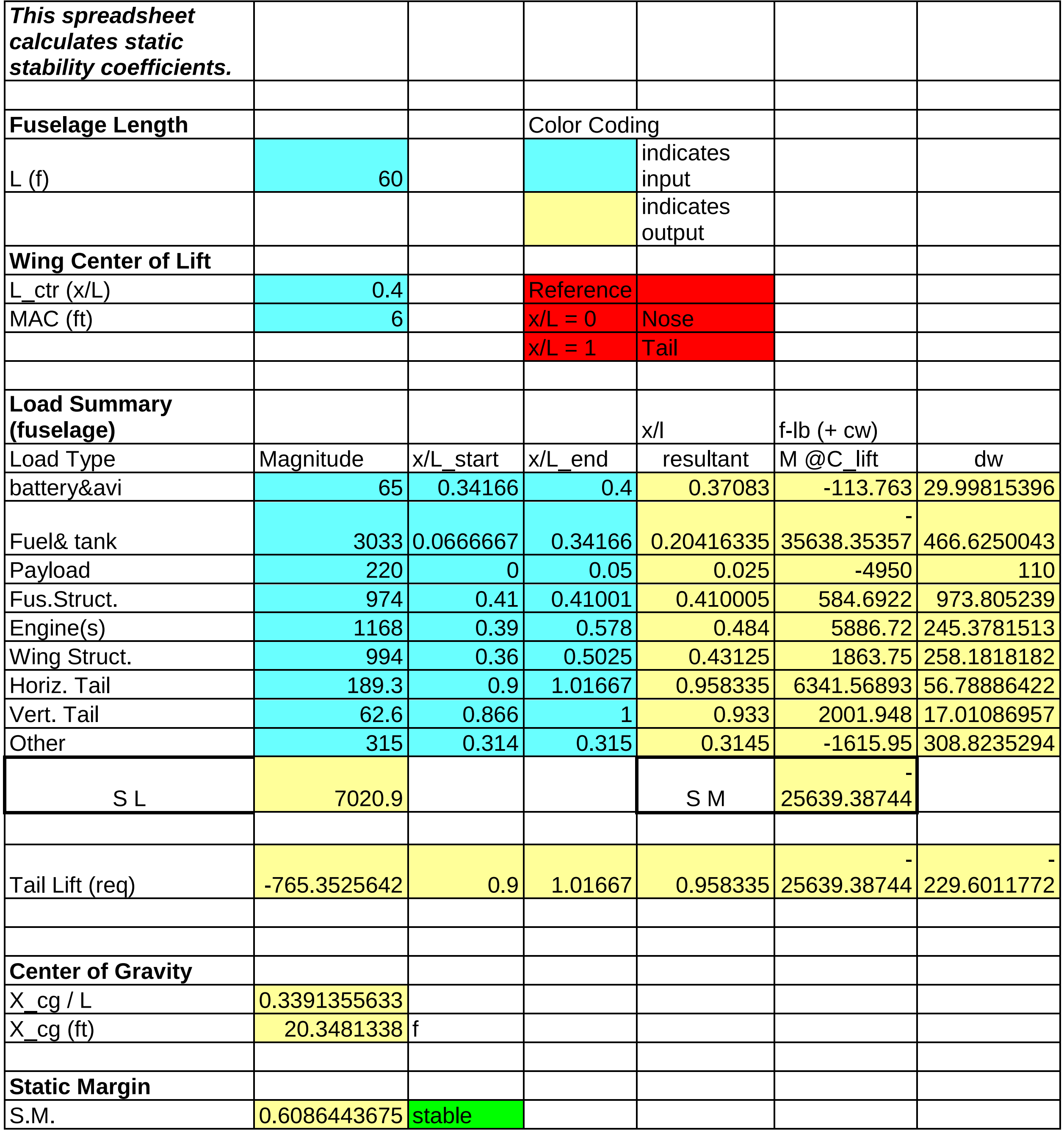
Fuel Amount and Burn

FlyP Address burns hydrogen gas (stored as a liquid cryogen) throughout flight with the majority expended during cruise at 60,000 feet. The eight-foot diameter tank stores 2111 pounds of hydrogen which will be exhausted after 320 hours of flight. Hydrogen fuel will be consumed at a rate of 6.6 pounds per hour or 0.11 pounds per minute during cruise.

CG Travel Plot, Stability and Static Margin

The following spreadsheet analysis yields static margin and stability envelope calculations. The takeoff stability is positive at 0.61 as is the point of minimum fuel at 0.1.

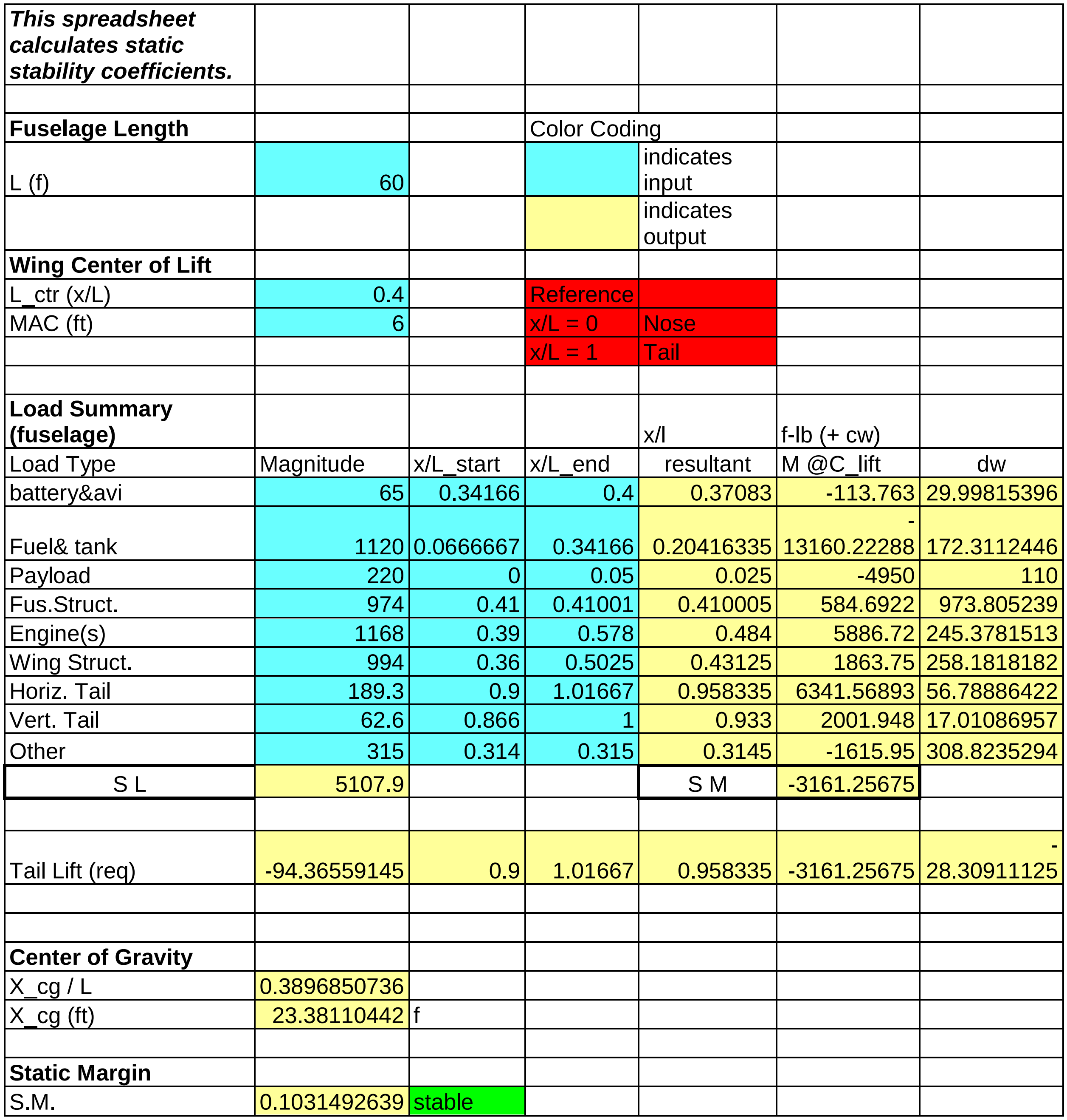
GTOW stability



This spreadsheet calculates static stability coefficients.						
Fuselage Length			Color Coding			
L (f)	60		🟦	indicates input		
			🟨	indicates output		
Wing Center of Lift						
L_ctr (x/L)	0.4		Reference			
MAC (ft)	6		x/L = 0	Nose		
			x/L = 1	Tail		
Load Summary (fuselage)				x/l	f-lb (+ cw)	
Load Type	Magnitude	x/L_start	x/L_end	resultant	M @C_lift	dw
battery&avi	65	0.34166	0.4	0.37083	-113.763	29.99815396
Fuel& tank	3033	0.0666667	0.34166	0.20416335	-35638.35357	466.6250043
Payload	220	0	0.05	0.025	-4950	110
Fus.Struct.	974	0.41	0.41001	0.410005	584.6922	973.805239
Engine(s)	1168	0.39	0.578	0.484	5886.72	245.3781513
Wing Struct.	994	0.36	0.5025	0.43125	1863.75	258.1818182
Horiz. Tail	189.3	0.9	1.01667	0.958335	6341.56893	56.78886422
Vert. Tail	62.6	0.866	1	0.933	2001.948	17.01086957
Other	315	0.314	0.315	0.3145	-1615.95	308.8235294
S L	7020.9			S M	-25639.38744	
Tail Lift (req)	-765.3525642	0.9	1.01667	0.958335	-25639.38744	-229.6011772
Center of Gravity						
X_cg / L	0.3391355633					
X_cg (ft)	20.3481338	f				
Static Margin						
S.M.	0.6086443675	stable				

Spreadsheet 9.1: Stability analysis for GTOW

Minimum fuel stability



This spreadsheet calculates static stability coefficients.						
Fuselage Length			Color Coding			
L (f)	60			indicates input		
				indicates output		
Wing Center of Lift						
L_ctr (x/L)	0.4		Reference			
MAC (ft)	6		x/L = 0	Nose		
			x/L = 1	Tail		
Load Summary (fuselage)				x/l	f-lb (+ cw)	
Load Type	Magnitude	x/L_start	x/L_end	resultant	M @C_lift	dw
battery&avi	65	0.34166	0.4	0.37083	-113.763	29.99815396
Fuel& tank	1120	0.0666667	0.34166	0.20416335	-13160.22288	172.3112446
Payload	220	0	0.05	0.025	-4950	110
Fus.Struct.	974	0.41	0.41001	0.410005	584.6922	973.805239
Engine(s)	1168	0.39	0.578	0.484	5886.72	245.3781513
Wing Struct.	994	0.36	0.5025	0.43125	1863.75	258.1818182
Horiz. Tail	189.3	0.9	1.01667	0.958335	6341.56893	56.78886422
Vert. Tail	62.6	0.866	1	0.933	2001.948	17.01086957
Other	315	0.314	0.315	0.3145	-1615.95	308.8235294
S L	5107.9			S M	-3161.25675	
Tail Lift (req)	-94.36559145	0.9	1.01667	0.958335	-3161.25675	-28.30911125
Center of Gravity						
X_cg / L	0.3896850736					
X_cg (ft)	23.38110442	f				
Static Margin						
S.M.	0.1031492639	stable				

Spreadsheet 9.2: Stability analysis for landing (minimum fuel)

From the above spreadsheet and the varying fuel weight with the respect, the following plot was generated to indicate the linear travel of the center of gravity as *FlyP Address* completes its mission.

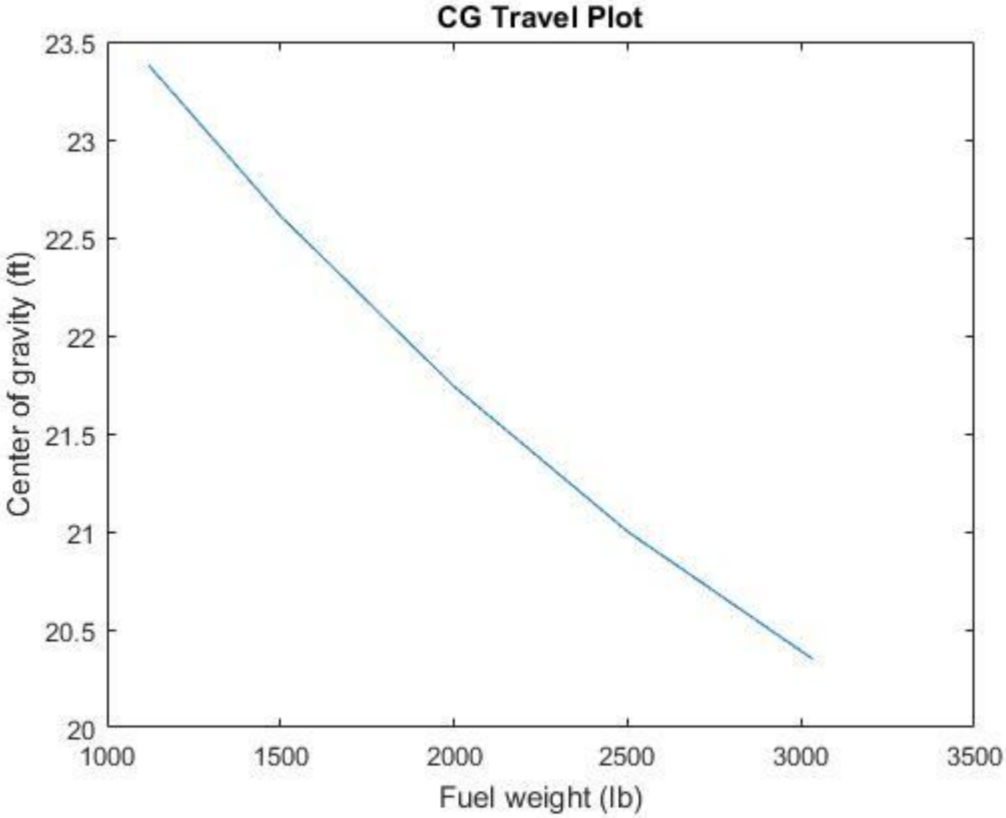


Figure 9.2: Center of Gravity shift throughout flight

CAD and Graphics

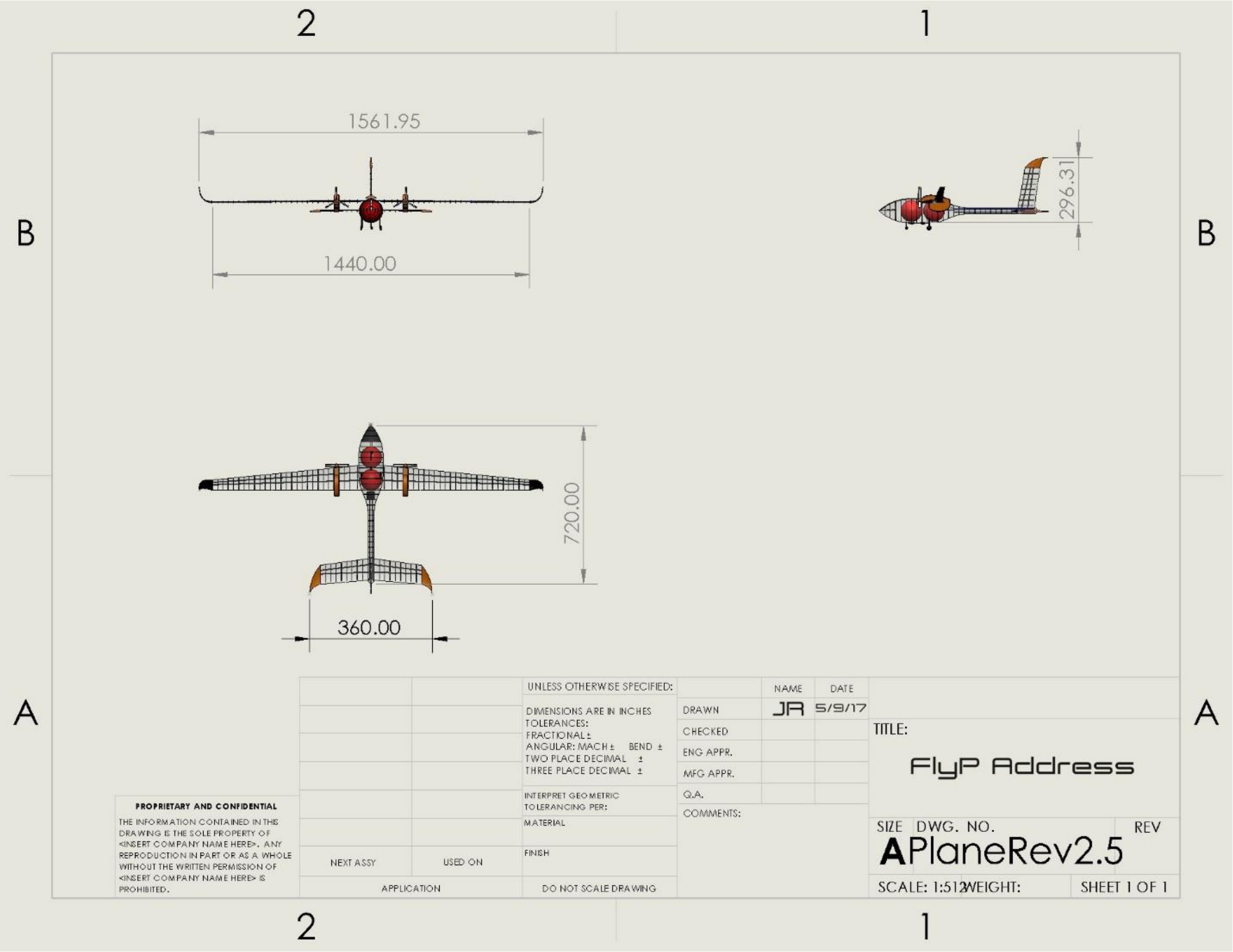


Figure 10.1: 3 View

Fuel placement, material breakdown, structural layout, payload configuration, and systems layouts were covered in previous sections throughout the report. To prevent redundancy, they have not been included a second time in this section.

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