ALL-WEATHER TAXI PILOTS

ATP-XW "BLIZZARD" PROGRESS REPORT

EAE 130A — SENIOR DESIGN

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Contents

List of Tables

List of Figures

1 Abstract

Urban Air Mobility (UAM) vehicles are intended as a means of rapid transport for people and goods in urban environments where travel times may be long due to high traffic. The E**x**perimental **W**eather aircraft ”Blizzard” (ATP-XW Blizzard) is designed for use in Chicago, a market challenging for UAM design, given the cities’ low temperatures, high wind speeds, and poor visibility during snow and rain. The ATP-XW Blizzard is therefore designed primarily to operate in the Chicago market, or other similar cold-weather cities. It is designed to carry a pilot and four passengers, and to service Chicago’s urban and suburban areas. The aircraft is designed for short ”hops”, to and from buildings, but is planned for a maximum flight range of at least 80 km. Initial mass calculations give an expected gross mass of 1740 kg, and plans to use a coaxial eight-rotor multirotor design. The aircraft additionally plans to use a hydrogen fuel cell system due to its greater range of temperature tolerance, as Li-ion batteries are prone to failure in cold weather. Future work will incorporate additional systems, such as sensor suites and de-icing technologies, to ensure robust resilience to adverse weather conditions.

Nomenclature

$(\frac{P}{W})_{to}$ .... Power to Weight Ratio During Takeoff

η_p .... Propeller Efficiency

η_{mech} .... Mechanical Efficiency

$\frac{C_L}{C_D}$ .... Lift to drag ratio

$\frac{W}{S_{disk}}$ .... Weight to Swept Area Ratio

γ .... Angle of Climb (with respect to horizontal)

$\hat{M}_{power\ plant,to,climb,loiter,landing}$ .... Minimum Required Mass of Power Plant For Takeoff Energy

$\hat{M}_{power\ plant,cruise}$ .... Minimum Required Power Plant Mass for Cruise Range

C_D .... Coefficient of drag

CCW .... Counter-clockwise rotating propeller

CW .... Clockwise rotating propeller

d_f .... Fuselage Diameter

E .... Endurance

$e_{specific}^{-1}$ .... Energy Density of Power Plant

l_f .... Fuselage Length

$L_{deficit}$ .... Lift Deficit

M .... Measure of Merit

M_{crew} .... Mass of crew

$M_{payload}$ .... Mass of Payload

$M_{power\ plant,\ to}$ .... Mass of Power Plant Required for Takeoff Power

$M_{structure}$ .... Mass of Air Frame

M_{total} .... Total Rotor Craft Mass

$P_{climb,to}$ .... Vertical Takeoff Phase Required Power

P_{climb} .... Climb Phase Required Power

P_{loiter} .... Loiter/Hover Phase Required Power

$P_{specific}$ .... Energy Density of Power Plant

R .... Range

S_{disk} .... Total Swept Disk Area of Rotors

t_{climb} .... Climb Phase Time

t_{hover} .... Hover Phase Time

t_{to} .... Takeoff Phase Time

UAM .... Urban Air Mobility

UAV .... Unmanned Aerial Vehicle

V .... Cruise Velocity

$W_{battery}$ .... Weight of battery

2 Introduction

2.1 General Problem Statement

The primary goal of UAM development is to provide a high throughput means of transportation in urban environments, where infrastructure costs are high, and dense population causes slow traffic. By transporting people and goods through light aircraft, it would be possible to reduce road traffic in a manner similar to that of a subway, bus, or light rail system. The UAM is therefore expected to serve as a means of rapid transportation, able to bypass road traffic, and deliver people or materials to and from buildings in an urban environment.

The ATP-XW Blizzard is expected to have a largely vertical flight profile, with short turnaround time, to exchange cargo. For a single tank of fuel, the aircraft is expected to travel from its fueling point to a landing point on a rooftop, and make several short ”hops”, delivering people from destination to destination, before returning to its fueling point.

2.2 Aircraft Mission

The ATP-XW Blizzard aircraft will serve as the fastest means of transportation in and between Chicago’s urban and suburban areas. It requires one pilot, carries a maximum of four passengers at a time, and can pickup and drop off anywhere within 50 kilometers of downtown Chicago. Designed to have a 80 kilometer range, it can do long haul trips, or many short transports between refuels. As a hydrogen powered aircraft, highly flammable propellant permits are required for its refueling locations. With jet fuel requiring the same permits, the initial refueling points for this aircraft will be the O’Hare International Airport, Midway International Airport, and Gary/Chicago International Airport. While not initially ideal, the design does not require significant upfront infrastructure investment. Optimized for unfavorable weather, this aircraft will serve as reliable on the spot transportation when most other air vehicles are grounded.

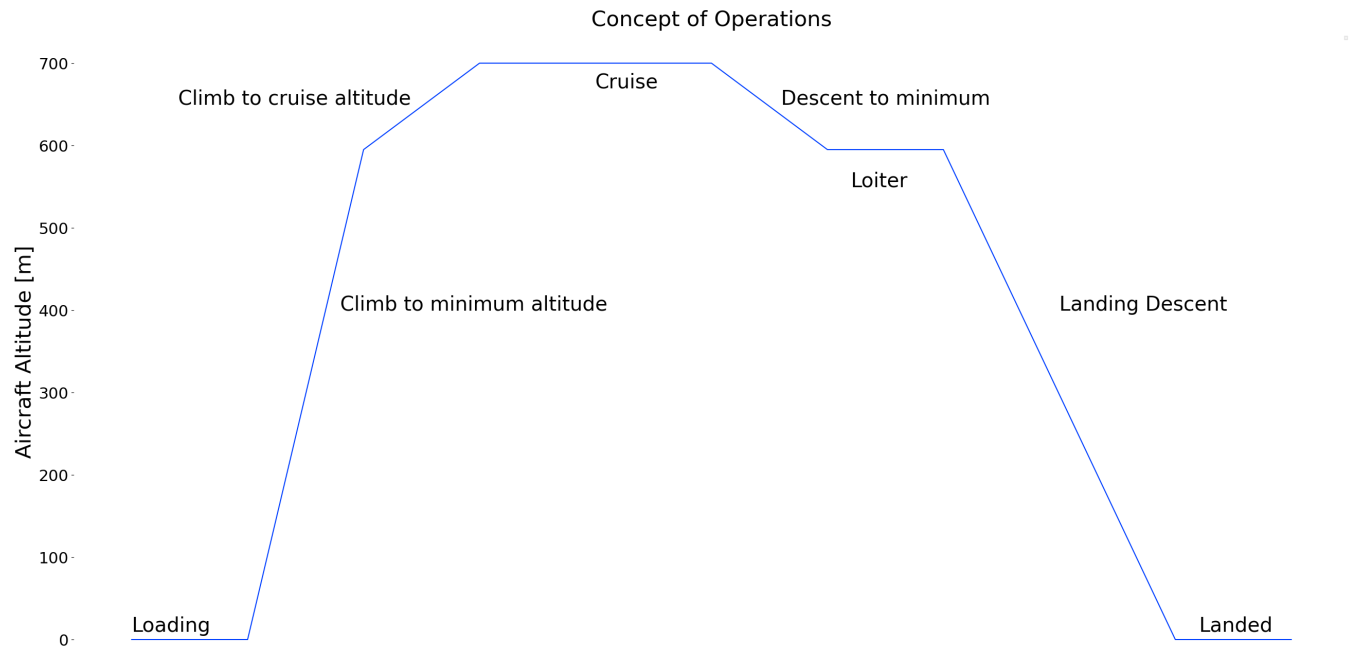


Figure 1: ATP Concept of Operations

A typical mission for the ATP-XW Blizzard begins by loading cargo, whether people or goods. The FAA requires that rotorcraft taking off in any city may only cruise at an altitude 500 ft above the highest point. In Chicago, the tallest building is Willis Tower at 442 m, which would require the minimum flight altitude to be 595 m. The ATP-XW Blizzard will vertically takeoff until it reaches its minimum altitude, and then climb to a cruise altitude of 700 m. After reaching its destination, the aircraft will descend to minimum allowable altitude to loiter, if the target landing site is currently occupied. It will then vertically land, and exchange cargo.

2.3 Aircraft Design Requirements

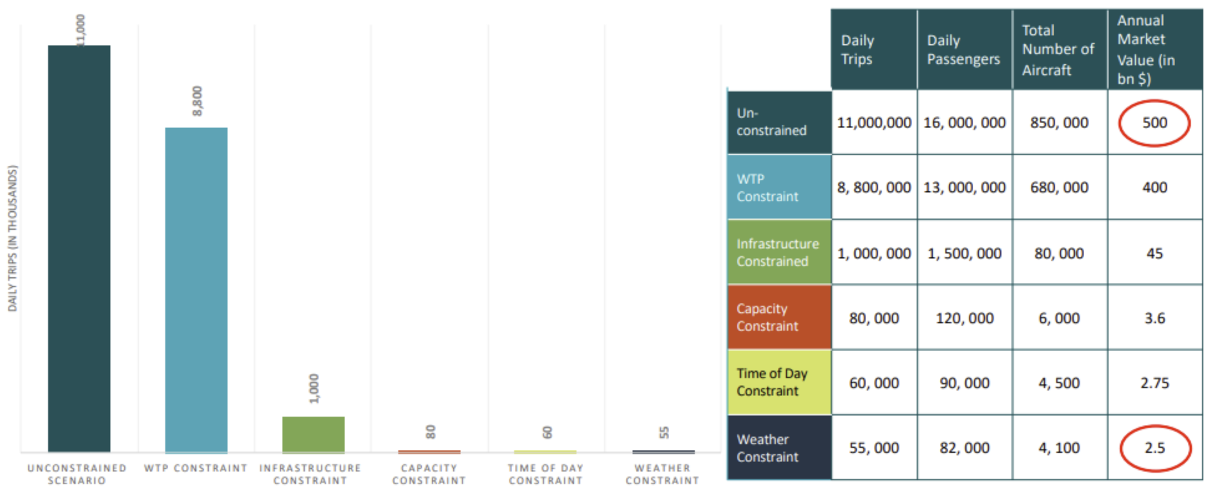
At the end of aircraft development, the aircraft shall meet the following requirements:

- The aircraft shall be capable of vertical takeoff and landing
- The aircraft shall be capable of human and autonomous piloting
- The aircraft shall carry 1 pilot and 4 passengers (80kg ea.) for a total maximum range of 80km
- The aircraft shall be capable of safe operation in temperatures greater than -20$^{\circ C}$, wind speeds less than 16 km/h, and in limited visibility conditions of greater than 1 km (fog conditions)
- The aircraft shall emit no criteria pollutants during operation

- The aircraft shall be capable of continued, operational flight in the event of a single rotor failure
- In event of catastrophic propulsion failure, the aircraft shall have a means of preventing loss of life

3 Market Study

With no specific data existing about UAM market projections in Chicago, a market summary[1] of 10 other major American cities was utilized for a best-estimate of future Chicago UAM operations, and assumed to be characteristic of most American cities. According to NASA's UAM market study, Air Taxi/Shuttle services are projected to achieve 0.1%-20% of all daily trips within the US. This large potential range demonstrates some of the current unpredictability of UAM demand, with weather and infrastructure restrictions accounting for the low-end of that projection as seen in Figure 2. Using the most constrained case of 55,000 trips per day, the UAM market still represents a potential $2.5 billion dollar market, with room for significant growth as engineering and infrastructure challenges are met.



	Daily Trips	Daily Passengers	Total Number of Aircraft	Annual Market Value (in bn $)
Un-constrained	11,000,000	16, 000, 000	850, 000	500
WTP Constraint	8, 800, 000	13, 000, 000	680, 000	400
Infrastructure Constrained	1, 000, 000	1, 500, 000	80, 000	45
Capacity Constraint	80, 000	120, 000	6, 000	3.6
Time of Day Constraint	60, 000	90, 000	4, 500	2.75
Weather Constraint	55, 000	82, 000	4, 100	2.5

Figure 2: Near-term UAM Market Size and Value. From Booz Allen Hamilton. "Urban Air Mobility (UAM) Market Study". In: (November 2018)

Early adopters of UAM services are projected to consist largely of business professionals comfortable with the increased cost of a novel air taxi system compared to that of car sharing or public transportation[2]. While this serves as an early constraint of an air taxi system, prices are expected to become competitive with common transportation methods as production and technologies reach scale[3].

As the number of daily UAM commuters increases, street-level traffic and the total number of cars in circulation is expected to decrease. This traffic off-load will directly lead to a decrease

[1] Booz Allen Hamilton. "Urban Air Mobility (UAM) Market Study". In: (November 2018).
[2] NASA. "Urban Air Mobility (UAM) Market Study". In: (October 2018).
[3] Hamilton, see n. 1.

in road congestion and the probability of road accidents. Additionally, as air taxi transport systems are overwhelmingly planned to utilize environmentally sustainable fuel sources, such as lithium-ion and hydrogen, this street traffic reduction will decrease net CO_2 emissions and lower the pollution of urban areas[4].

While UAM services offer a number of benefits, there are also significant engineering and infrastructure challenges to overcome. Paramount is the safety of both passengers and the populations along intended flight paths. While precautions must be taken to guarantee passenger safety in the event of failure, risk calculations must also account for the safety of populated areas in the event of a crash. It is equally important to build public trust for both UAM technology, both for autonomous and piloted vehicles. It is only then that the public will begin to widely adopt UAM travel.

However, as mentioned earlier, cost will be a negative factor in the early stages of adoption, limiting the quantity of passengers. Given the flammability permits required for H_2 fuel, the aircraft will be expected to travel to airports to refuel. While still able to load and unload cargo on rooftops or any open area, an initial lack of infrastructure will increase initial operating costs. The costs are expected to fall as local governments invest in infrastructure for refueling of aircraft on rooftops[5].

In conclusion, the UAM market is viable, but still in its preliminary stages, and there are a multitude of challenges that must be solved before public use. Based on the NASA UAM study, and assuming levels of investment in Chicago to be consistent with other major cities in the US, this market study concludes that UAM transportation will be a slow-growing, yet highly profitable industry, able to compete with popular means of urban transport, such as ride-shares and other means of public transportation.

[4]Hamilton, see n. 1.
[5]Hamilton, see n. 1.

4 Competing Designs

Table 1: **COMMON GENERAL AVIATION AIRCRAFT SPECIFICATIONS**

AIRCRAFT	NUMBER OF PASSENGERS	RANGE (KM)	WEIGHT (KG)	MAX SPEED (KM/H)
Joby S4	4	241	1815	322
Hyundai S-A1	4	97	N/A	290
Volocopter	1	35	450	110
EHang 184	1	35	360	130
EHang 216	2	35	620	130

Currently in the UAM market, many new and upcoming companies are showing off a variety of concept designs and prototypes. The JobyS4, originally known as ”Uber Elevate”, is the most developed concept listed in Table 5. This aircraft proved to be a promising design after completing a 15 minute test flight while suspended from a helicopter in 2020. Joby Aviation is focusing on streamlining daily travel for passengers in crowded cities, and their main mission statement is to provide a clean and quiet, electrically-driven rotor craft that they claim will transform the taxi market[6].

The Hyundai S-A1 is relatively newer player in the market. They are currently in their concept/design phase, but are planning to conduct their first test flight no earlier than 2023. The SA-1 is designed to be driven by electric motors, aiming to reduce noise and emissions. The purpose of this aircraft is to also shorten transit times within urban areas for daily commuters. Hyundai is offering more personalized versions of their rotor craft to autonomously perform certain tasks. This is aimed at aiding in food or medicine deliveries, as well as urgent transport in medical situations[7].

The Volocopter is a single-seat, all-electric rotor craft that can be either piloted or flown autonomously. Something notable about this aircraft is its power plant, which consists of 18 small brushless DC motors. This aircraft is focused on personal use, and, similarly to its competition, its primary goal is to ease commuting in crowded urban areas. The Volocopter proved itself when it made its first flight in2016. The company is planning to launch an air taxi service in Singapore[8].

Finally, EHang falls into a similar category as the Volocopter. This company is focused on more personalized aircraft that are capable of carrying 2 passengers (184 and 216 models). EHang also wants to reduce travel times in crowded cities by introducing a fleet of autonomous air taxis. The company has completed multiple successful test flights in order to refine their autonomous flight algorithms. More recently, they adapted their 216 model to fight high-rise fires in cities. EHang is currently the leader in autonomous AI algorithms dedicated to UAM flight.[9].

[6] *Joby-S4*. URL: https://evtol.news/joby-s4/.
[7] *Hyundai-S-A1*. URL: https://evtol.news/hyundai-s-a1/.
[8] *Volocopter*. URL: https://evtol.news/volocopter.
[9] *Ehang*. URL: https://evtol.news/ehang/.

While the current UAM/eVTOL vehicle market displays a wide variety of design configurations, all competitors discussed in this section plan to utilize lithium-ion power plants. This shared decision is likely driven by the relatively high maturity level of Lithium-ion technologies and its heritage in existing electric vehicles. Despite this prevalence, lithium-ion batteries represent a number of challenges for UAM operations due to their low energy density, significant weight, poor cold weather performance, long charging duration, and environmental issues arising from Lithium mining. These performance worries have lead to some smaller UAM/eVTOL companies designing with alternative energy sources in mind, such as hydrogen fuel cells[10][11], for increased efficiency.

5 Initial Aircraft Sizing

In order to ensure that our aircraft preliminary size is reasonable, we used power requirements for each phase of flight in order to evaluate the requirements of our power plant. Using this information we can then ensure that the aircraft size that we are proposing is feasible with current technology.

5.1 Cruise Performance

The first phase of flight used to determine the ATP-XW Blizzard's power plant requirements is cruise. One of the aircraft's design parameters is having a range of 80 kilometers. Although the aircraft will be more optimized towards take off and climb, we used this range requirement as a starting point for the iterative process which will determine the power plant weight of the ATP-XW Blizzard. A MATLAB script with the following inputs was used to determine the weight of the power plant required for the aircraft to cruise for 80 kilometers:

Table 2: **CRUISE PERFORMANCE INPUTS**

PARAMETER	VALUE	UNIT
c_1	960	Wh/kg
η_{mech}	0.81	—
R	80	km
η_p	.8	—
$\frac{C_L}{C_D}$	16	—
$W_{structure}$	9810	N
W_{crew}	3924	N
$W_{payload}$	981	N

The value for the power plant energy density c_1, is for Hypoint inc.'s Turbo air-cooled HTPEM

[10] *Bartini Website*. URL: https://bartini.aero/.
[11] *Vertiia Website*. URL: https://www.vertiia.com/.

(High Temperature Proton Exchange Membrane) fuel cell power plant[12]. All other values were determined by comparing values for competing designs to our own aircraft.The equation used to calculate the preliminary power plant weight is as follows:

$$W_{power\ plant} = \frac{W_{rest}}{\frac{\eta_p}{R}\frac{C_L}{C_D}\frac{c_1}{g} - 1} \tag{1}$$

Where,

$$W_{rest} = W_{structure} + W_{crew} + W_{payload} \tag{2}$$

The weight calculated for the aircraft's power plant was then added to W_{rest}, and used to determine the amount of extra power plant weight required to climb, loiter, and land. After a power plant weight value was calculated for those flight phases, they were added to the W_{rest} value in the calculations for the weight required for cruise, and the iterative process continued.

[12]Alex Ivanenko. "Technical White Paper". In: (September 2020).

5.2 Climb, Loiter, and Landing Performance

In order to gauge the size of the power plant to provide sufficient power throughout all phases of flight, we need to also analyze the power consumption during the most critical phases of flight: takeoff, climb, descent, loiter, and landing. Here a MATLAB script was written based on the equations found in a UAM/eVTOL sizing document[13].

Table 3: **CLIMB AND LANDING PERFORMANCE INPUTS**

PARAMETER	**VALUE**	**UNIT**
W_{togw}	15205	N
η_{mech}	0.81	—
$e^{-1}_{specific}$	960	Wh/kg
$P_{specific}$	960	Wh/kg
f	0.320	m/s
M	0.7	—
S_{disk}	200	m^2
ρ_∞	1.225	kg/m^3
η_p	0.8	—
e	0.85	—
$v_{climb,to}$	10	m/s
t_{to}	63	s
t_{climb}	20	s
t_{hover}	10	s
v_{climb}	11.3	m/s
$D_{climb,to}$	595	m
D_{climb}	105	m
γ	0.471	rad
C_D	0.035	—
$L_{deficit}$	3801.375	N

We first calculate the required takeoff power using the following equation:

$$P_{climb,to} = \left(\frac{1}{\eta_{mech}}\right)\left(\frac{W_{togw}v_{climb,to}}{2} + \frac{fW_{togw}}{M}\right)\sqrt{\frac{fW_{togw}}{2S_{disk}\rho_\infty}} \tag{3}$$

Next we can calculate the power required for the given hover time using the following relation

$$P_{hover} = \left(\frac{1}{\eta_{mech}}\right)\left(\frac{fW_{togw}}{M}\right)\sqrt{\frac{fW_{togw}}{2S_{disk}\rho_\infty}} \tag{4}$$

Next, we can find the climb power, here we are taking into account the fact that the rotor craft is no longer climbing vertically (as it would during takeoff) but rather with a horizontal velocity

[13] Daniel P. Raymer. “Aircraft Design: A Conceptual Approach”. In: (2018).

component. For the given climb time the following equations can be used to find the power requirement for this phase of flight

$$D_{climb} = \frac{1}{2}\rho_\infty v_{climb}^2 S_{disk} C_D + W_{togw}\, sin\,\gamma \tag{5}$$

$$P_{climb} = \left(\frac{v_{climb}}{\eta_p}\right)\left[D_{climb} + \frac{L_{deficit}}{2e\rho_\infty v_{climb}^2 S_{disk}} + W_{togw} sin\gamma\right]\left(\frac{1}{\eta_{mech}}\right) \tag{6}$$

We then find the energy required for each segment of the flight by the following relation

$$E_{seg} = P_{seg} t_{seg} \tag{7}$$

We can then find the battery weight contribution for all of these phases of flight using

$$W_{battery} = \frac{(\sum E_{seg})}{e_{specific}^{-1}} \tag{8}$$

This can then be added to the cruise flight phase battery weight to find an overall power plant weight required to hold enough energy to complete an 80 km mission. Using these numbers we can then iterate on our initial design to ensure that the aircraft weight and concept of operations are feasible with current power technology.

5.3 Overall Performance and Preliminary Total Weight

The resulting battery weight from equation 10, combined with the battery weight required to satisfy the cruise range from 1 was about 30 kg. This results in a power train which can only supply about 60 kW of power, where the aircraft needs upwards of 380 kW to take off vertically with a 30 kg power train. This phenomenon shows that the driving factor for the weight of the power train in the ATP-XW Blizzardis not its range, but its power required for take off. With this in mind, the weight of the power train $M_{power\ plant}$,was iterated until the power required of the power plant at take off was less than the possible power output of the power plant by about 10 kW. After calculating the power train weight required for take off, the battery weights required to satisfy the energy requirements of a 80 km mission were re-calculated and are presented as $\hat{M}_{power\ plant,\ cruise}$, and $\hat{M}_{power\ plant,to,\ climb,\ loiter,\ landing}$ in the performance table below. Since the sum of these values are significantly less than the mass of the power train, we proceeded to calculate what the range and endurance of our aircraft would be on its longest range mission with only one take off and landing. The following equation was used to determine the cruise range of the vehicle, with E as $e_{specific}^{-1}$ of the power train, multiplied by the mass of the power train less the portion of the power train required for take off and landing:

$$R = \eta_p \frac{C_L}{C_D}\frac{E}{W} \tag{9}$$

The follow equation was used with cruise speed of 33.3 m/s to determine the endurance of the aircraft:

$$E = \frac{R}{V} \tag{10}$$

Table 4: **OVERALL PERFORMANCE AND PRELIMINARY TOTAL WEIGHT**

PARAMETER	**VALUE**	**UNIT**
$\hat{M}_{power\ plant,\ cruise}$	31.43	kg
$\hat{M}_{power\ plant, to,\ climb,\ loiter,\ landing}$	1.81	kg
$M_{power\ plant,\ to}$	240	kg
M_{crew}	400	kg
$M_{payload}$	100	kg
$M_{structure}$	1000	kg
M_{total}	1740	kg
$P_{available}$	480	kW
$P_{climb,to}$	470.35	kW
P_{climb}	117.14	kW
P_{loiter}	39.40	kW
$(\frac{P}{W})_{to}$	275.86	W/kg
$(\frac{W}{S})_{to}$	8.7	kg/m^2
R_{cruise}	705	km
E_{cruise}	5.9	hrs

Looking at the results in the table above, we can see that the final estimated gross takeoff weight of the rotor craft is 1740 kg, with a 240 kg power plant. Due to the high energy density of HyPoint's fuel cell system, 240 kg of power affords the aircraft a very long range and endurance time. Those values are calculated for cruise only, so the range of the aircraft will decrease significantly when it is making the frequent landings it is designed for. That said, it may be useful to have a smaller hydrogen tank on board, while still keeping the number of fuel cells required to supply power for takeoff.

6 Aircraft Layout

The Chicago market presents a hostile weather environment for VTOL UAM, and a multitude of market-specific design considerations must be made.

6.1 VTOL Design Considerations and Requirements

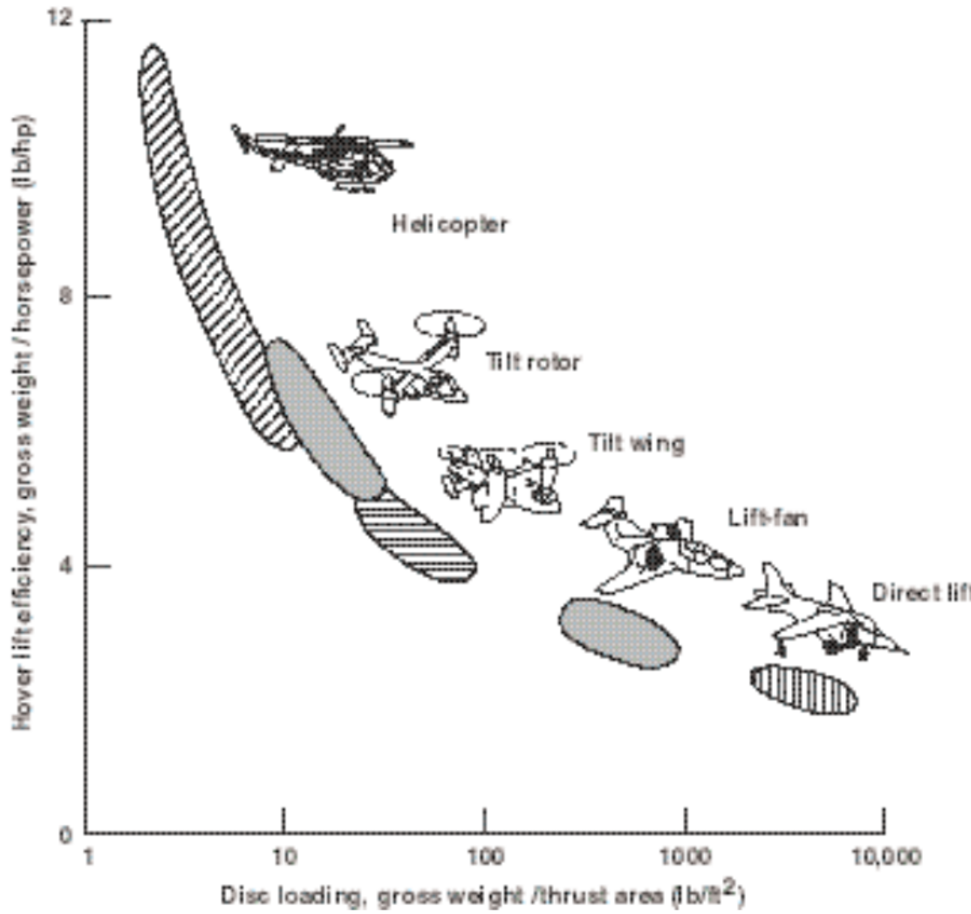


Figure 3: Plot of hover efficiency vs. rotor disk loading. From Daniel C. Dugan Martin D. Maisel Demo J. Giulianetti. “The History of the XV-15 Tilt Rotor Research Aircraft: From Concept to Flight”. In: (2000)

Given the largely vertical flight profile, with a relatively short cruise time, the aircraft is to be optimized for hover efficiency, rather for lift to drag in flight. The hover efficiency of a rotorcraft is proportional to the square root of the rotor loading on the propellers[14], and therefore low rotor loading is desirable to optimize efficiency, and to reduce power required for the aircraft. To achieve this, either a small number of large rotor disks is required, which increases the disk size,

[14] D. Felix Finger. “Comparative Performance and Benefit Assessment of VTOL and CTOL UAVs”. In: (September 2016).

or a large number of small rotor disks is needed, to distribute the load across additional rotor disks.

To meet design requirements for lower carbon and noise emissions, the aircraft must use an electric motor to power the rotors. While a helicopter configuration would be optimal for lower rotor loading, current electric motors available on the market do not produce sufficient torque to power an aircraft an aircraft with the specifications set out in the previous section. To maintain low rotor loading, a multicopter configuration must be used instead to distribute the load across multiple rotors.

6.2 Rotor Configuration

While currently popular due to their mechanical simplicity, multicopter designs come with a multitude of unique problems and requirements. Yaw control is achieved by varying the rotational speed of CW and CCW motors to achieve a net torque on the aircraft, which is only possible using an even number of rotor disks. Yaw control is possible on a multirotor design with an odd number of propellers, but requires a mechanism to tilt one of the rotors, adding additional weight and mechanical complexity, and therefore the ATP-XW Blizzard must use an even number configuration.

The number of motors used is another consideration. Four propellers is the minimum number required for three-axis control, but a motor failure would result in the loss of control of all three axes, and the loss of the aircraft. For a six rotor aircraft, a rotor failure would cause a loss of only yaw control. An eight rotor aircraft can experience a rotor failure without loss of control. The ATP-XW Blizzard will therefore use a minimum of eight rotors as a safety requirement.

Having decided the number of rotors, the only question that remains in regards to rotor configuration is *where* and *how* to place them. Placing all eight rotors in the same plane will require smaller rotors (increasing disk loading), and will significantly increase aircraft size, which is undesirable. A coaxial configuration (four sets of stacked rotor pairs) will allow for a larger rotor size (reducing disk loading), at the cost of reduced propeller efficiency η_p. To maintain higher hover efficiency, the aircraft will therefore use a coaxial rotor configuration. To allow for easier boarding of the aircraft, the rotors will be attached to the top of the aircraft.

6.3 Preliminary Configuration

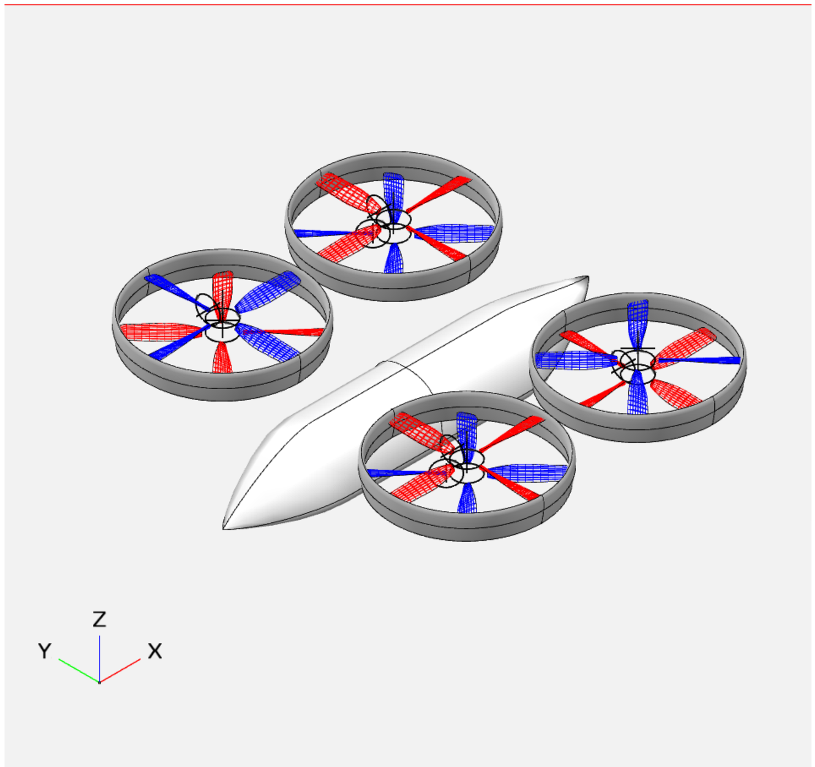


Figure 4: Preliminary UAM design, modelled in OpenVSP. Clockwise rotating propellers in blue, counterclockwise in red.

The ATP-XW Blizzard will consist of a single body fuselage, with a cockpit at the front of the aircraft, and a larger passenger compartment to the rear of the aircraft. It will be propelled by eight rotors, in a coaxial configuration, positioned at the top of the aircraft. Passengers will be able to enter and exit the cabin through a door at the rear of the fuselage. The eight rotor configuration allows for safe operation of the aircraft in the event of rotor failure, and a parachute system is included in the event of catastrophic failure.

The initial sizing dimensions of the rotor craft are listed in the following table

Table 5: **Preliminary Fuselage Sizing**

Parameter	Value	Unit
l_f	7	m
d_f	2	m

As the design process progresses, the design team anticipates trade studies on:

- The addition of a blended-body lifting surface to which the rotor ducts are mounted, with the intent of creating lift during cruise

- A staggered rotor configuration, with an additional high aspect ratio wing to create lift during cruise
- De-icing technologies for flight in cold weather environment
- Various sensor packages to allow the aircraft to navigate in a low-visibility environment (i.e. Chicago during rain/snow)

7 Key Technologies

The electric power seems to be the most popular and promising alternative to hydrocarbons. However, hydrogen fuel is starting to see some momentum, due to the recent interest and research. As well as environmentally sustainable, and relatively abundant, hydrogen also highly energy dense. But crucially, given the main design concern is Chicago's more extreme weather conditions, hydrogen is far more tolerant to temperature extremes than competing Li-ion batteries. A comparison of the two, conducted by HyPoint, and shown in Figure 5, provides a visualization of the energy density and the specific power of HyPoint Turbo Air-Cooled cells, with respect to a comparable liquid-cooled system, or to conventional Li-ion batteries[15].

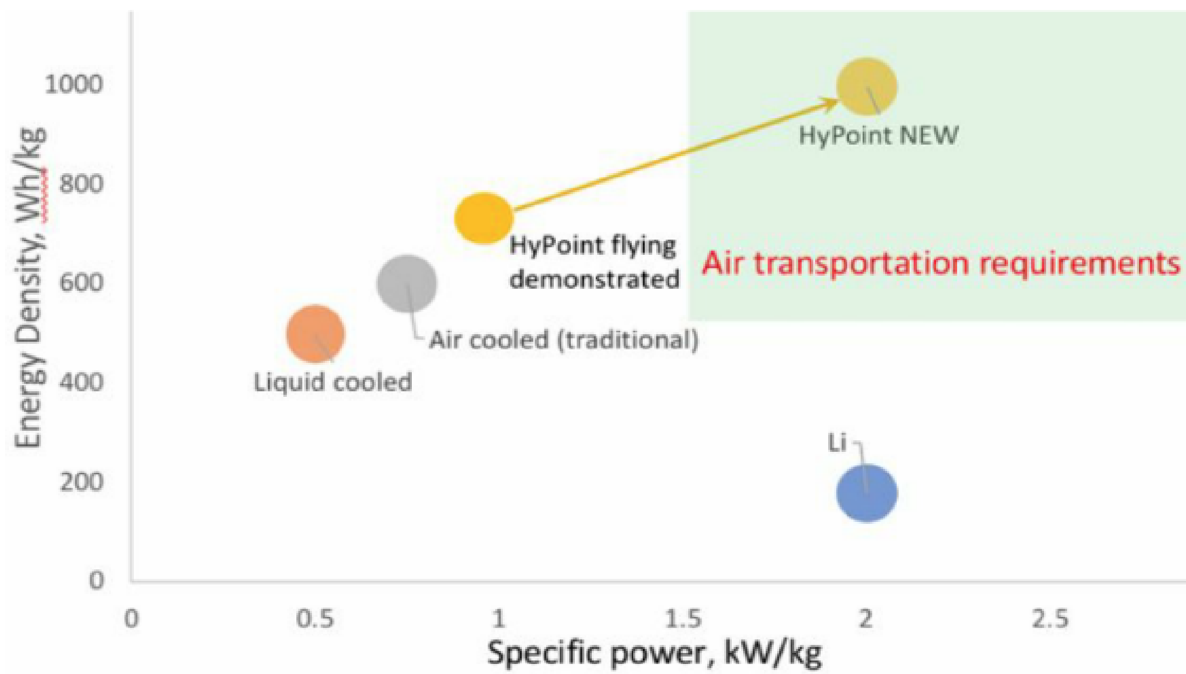


Figure 5: Energy density and specific power comparison between HyPoint fuel cell systems and other systems. From Brian Garrett-Glaser. "Will Hydrogen Fuel Cells Play a Role in the VTOL Revolution?" In: (April 2020)

The ATP-XW Blizzard uses the HyPoint Turbo air-cooled HTPEM[16] fuel cell system for its

[15] Loz Blain. "HyPoint's turbo fuel cells promise huge range and power for eVTOLs". In: (May 2020).
[16] Ivanenko, see n. 12.

power train. With a specific power of 2000 W/kg and a specific weight of 960 Wh/kg, this system is far lighter than any other electric power train. The HyPoint Turbo air-cooled HTPEM fuel cell system is also ideal for use in harsh weather conditions. HTPEM fuel cells are designated “High Temperature”, because of the excess heat they produce as they convert hydrogen into water and electric power. This excess heat is transformed into usable energy by HyPoint’s air-cooling system, but it also protects the fuel cells from any adverse effects caused by a low temperature environment, in effect providing its own heating system. In fact, the combination of high excess heat and advanced cooling system present in the power train gives it an impressive -60°to 60°Celsius range of operative temperatures. Comparable Li-ion batteries have been shown to have lower output voltages and accelerated battery degradation at similar, sub-zero temperatures[17]. Li-ion batteries are therefore inviable for operation in a cold-weather market such as Chicago. The use of HTPEM in the ATP-XW Blizzardallows it to operate in extreme weather conditions without complex, heavy, and highly energy demanding temperature regulation systems[18].

The refueling time for a hydrogen powered vehicle is also markedly superior to other electric vehicles. While lithium-ion batteries take 30 minutes to several hours to charge[19], estimated refueling of a hydrogen powered aircraft will take approximately 10 to 20 minutes[20]. The drawback for refueling with hydrogen is that it requires high flammable propellant permits at its refueling locations. This limits the refueling *locations* for the aircraft, but there are a number of airports around Chicago which *already* have the permits required for their jet fuel use. However, frequent refueling of hydrogen power cells does not present a risk, unlike lithium-ion batteries, which deplete their own battery life and maximum power with frequent recharging. Therefore, a hydrogen fuel system results in not only faster refueling, but also a more durable power system.

[17] et. al. Dongxu Ouyang Yaping He. “Influence of low temperature conditions on lithium-ion batteries and the application of an insulation material”. In: (2019).

[18] Blain, see n. 15.

[19] *Charging Lithium-ion*. URL: https://batteryuniversity.com/learn/article/charging_lithium_ion_batteries.

[20] Ivanenko, see n. 12.

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[1] *Bartini Website*. URL: https://bartini.aero/.

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9 Appendices

9.1 Initial Mass Sizing Script

```
%battery weight requirment for 80 km rang
clear;
g=9.81;

%input values
M_bat_to_l=240; %kg
W_bat_to_l=M_bat_to_l*g; %N

%known values
specific_stack_power=2000; %W/kg
energy_density=960*3600; %Wh(*3600)/kg (h2 tank included)
elec_to_mech=.81;
range=80000; %m
prop_efficien=.8;
Cl_o_Cd=16;
W_crew=80*5*g; %N
W_struct=1000*g; %N
W_payld=100*g; %N

%resulting values
W_rest=W_struct+W_crew+W_payld;
W_bat_range=(W_rest+W_bat_to_l)/((prop_efficien/range)*...
    (Cl_o_Cd)*(energy_density/9.81)-1);
M_bat_range=W_bat_range/g;

%Range and Endurance
Energy=energy_density*(M_bat_to_l-1.8146);
R=prop_efficien*(Cl_o_Cd)*(Energy/(W_rest+M_bat_to_l));
Endure=(R/(33.33))/3600;
```

9.2 Take-off, Climb, Loiter, and Landing Requirements and Sizing Script

```
clear;
g=9.81;

%inputs
```

```
Full_bat_m=240; %kg
M_togw=1500+Full_bat_m; %kg
Wtogw=M_togw*g; %N

%constants
mech_effic=.81;
engergy_density=960*3600; %Wh(*3600)/kg (h2 tank included)
specific_power=2000; %W/kg
fus_downwash=.314+.006; %m/s
M=.7; %measure of merit %slide 18 Feb 3rd says typical is .7
Swept=200; %m^2
rho=1.225; %kg/m^3
prop_eff=.8;
e=.85; %oswald

%takeoff power
v_up=10;
% P_up=zeros(length(v_up),1);

P_up=(1/mech_effic)*((Wtogw*v_up)/2+(Wtogw*fus_downwash)/M)*...
    sqrt(fus_downwash*(Wtogw/Swept)/2*rho);

%hover power
P_hover=(1/mech_effic)*((Wtogw*fus_downwash)/M)*...
    sqrt(fus_downwash*(Wtogw/Swept)/2*rho);

%climb power
v_climb=11.3; %m/s
climb_ang=.471; %radians

C_d=.035;
L_def=.25*Wtogw; %N

D_climb=.5*(rho*v_climb^2*Swept*C_d)+Wtogw*sin(climb_ang);

P_climb=(v_climb/prop_eff)*(D_climb+L_def/(4*.5*e*rho*v_climb^2*Swept));

up_time=60*2;
climb_time=20*2;
hover_time=10;

E_up=P_up(1)*up_time;
E_climb=P_climb*climb_time;
E_hover=P_hover*hover_time;
```

```
W_bat=(E_up+E_climb+E_hover)*(1/engergy_density);
M_bat_rang=W_bat/g;


%take off performance
Swept=200; %m^2

P_up_available=specific_power*(Full_bat_m);

P_W=P_up_available/M_togw;
W_s=M_togw/Swept;
```