Preliminary Design Report

Group 10: Megatron

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The mission and key parameters come from the Vertical Flight Society (VFS) competition guidelines. Among these include that the design is VTOL-capable while having a cruise speed of 833 km/h at an altitude of 6096 m and it has the ability to carry a 2712 kg payload in a 1.98 m × 2.43 m × 9.14 m space. Its mission radius is 926 km and there is an emphasis on minimizing downwash during VTOL operations.

The primary market for our aircraft would be the military, as the VFS competition focuses on designing an aircraft that the military would find useful. However, a civilian market could also be targeted, as a conversion from cargo to passenger could be accomplished, allowing our aircraft to serve in the regional air mobility domain.

As the military is the intended buyer, various military crafts serve as competitors to our aircraft design. VTOL aircraft such as the V-22 Osprey are already in-use by the military, and heavy-lift helicopters such as the CH-47 Chinook are capable of carrying heavy loads with a vertical takeoff and landing. There are also aircraft under development such as the V-280 Valor, capable of VTOL flight. Unlike the competition, however, our aircraft will have the advantage of being able to carry payload, take off and land vertically, and fly at a fast cruise speed that is comparable to a traditional airplane.

Requirements and Mission

Aircraft Requirements

Crew	3 people, 250 lbs each
Limit Load Factor	3.5g
Weight Contingency	5%
Landing Gear Sink Speed	3 m/s @ ⅔ rotor lift

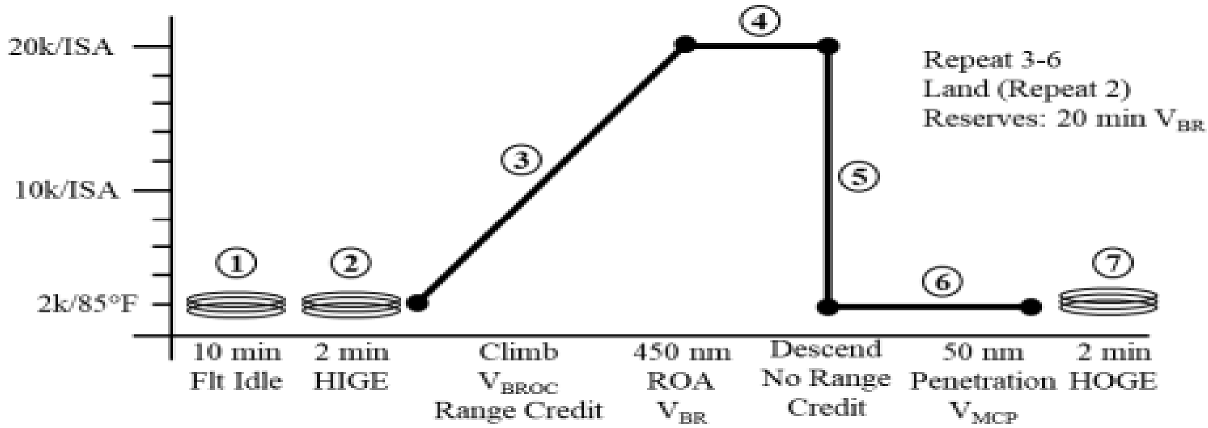
Mission Requirements

Mission Parameters	Value (Imperial)	Value (SI)
Payload Weight	5,000 lbs	2,268 kg
Mission Equipment Package	1,000 lbs	453.592 kg

Cargo Bay Dimensions	6.5 × 8 × 30 ft	1.98 × 2.43 × 9.14 m
Cruise Speed	450 KTAS	833.4 km/hr
Minimum Cruise Height	20000 ft	6,096 m
Mission Radius	500 nmi	926 km

Mission Profile

Section	Time [min]	Speed [km/hr]	Distance [km]	Description
Flight idle	10	0	0	10 minute flight idle
HIGE	2	0	0	2-min Hover In Ground Effect (HIGE) takeoff
Climb	6.35	400	42.33	Cruise-climb at best climb speed (VBROC) where range credit may be taken for the total Radius of Action (ROA) in Segments 4 and 6
Cruise	56.95	833	790.67	Cruise 450 nm (833 km/h) at be no less than 20,000 ft (6,096 m) ISA conditions or best cruise altitude at the best range speed (VBR) or no less than 450 KTAS (833 km/hr)
Descent	4.27	400	(28.47)	Descend to 2,000 ft MSL 85°F (no range credit may be taken)
Penetration	13.89	400	92.6	50 nm (92.6 km) of low-altitude, high-speed penetration
HOGE	2	0	0	2-min mid-mission Landing Zone (LZ) Hover Out of Ground Effect (HOGE) at Mid-Mission Gross Weight (MMGW). Segments 3-6 are repeated, followed by a 2 min HOGE landing segment. Fuel/Energy reserves shall be 20 min at VBR and 2k/85°F.
Total*	180.92	–	1851.2**	(*Total include the repeats) (**Descent range not included in total range)



Configuration

These mission requirements—VTOL operation while at the same time achieving a high cruising speed—forced us to take many considerations when deciding our aircraft configuration. Because of the need to reduce drag during cruising conditions, a permanent upward facing lift system was not considered, as it would be unused during cruise flight and simply generate unnecessary drag. As a result, the first configuration decision that needed to be made was whether to use a tilt-rotor design or a tilt-wing design.

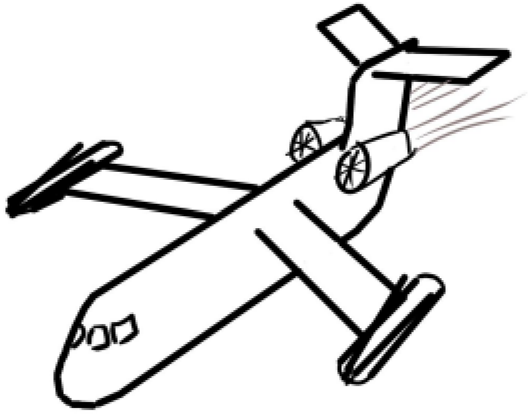
Ultimately, a tilt-rotor design was decided upon because the wings remain horizontal in a tilt-rotor aircraft, which allows the aircraft to generate lift through horizontal motion even before the rotors have rotated completely. Additionally, the wings would not have to be as complex, as the wings can remain fixed to the fuselage and not have to be designed to be able to rotate.

The second configuration decision that we made was regarding the propulsion system. Because the VFS competition specifies that the downwash during VTOL operations should be minimized, large helicopter-like rotors were decided upon for the tilt-rotors. However, because of the desired high cruise speed of 833 km/h, an airscrew for propulsion during cruise flight was considered to be inappropriate. Instead of receiving horizontal thrust through its tilt-rotors, it was found that it was better to generate thrust through two turbofans. In order to avoid hazardous situations to ground crew during VTOL, and to avoid the ingestion of foreign object debris into the turbofans when hovering close to the ground, the engines must be aft-mounted. This allows the turbofans to be situated high above the ground and so it would avoid these issues.

For the tilt-rotors, we had to decide whether or not they would be powered with a turboshaft engine or by using electric motors. A turboshaft engine would generate enough torque to power the craft while using fuel to operate—just like the two turbofans—which reduces the need for multiple types of energy storage. An electric motor, on the other hand, requires heavy batteries to be added to the aircraft and reduces the amount of time that the aircraft can spend hovering. However, we ultimately decided to power the tilt-rotors with electric motors because the tilt-rotors are only used during VTOL operations. They are not used during cruise flight, which is the majority of the mission. If the tilt-rotors were powered through engines, then the heavy engines are dead weight for most of the mission, and they would need to be stopped and started during the flight, which may not be reliable or responsive enough. An electric motor can be started and stopped with no need to have a startup process.

Because of the separation of VTOL and horizontal propulsion, each can be optimized for their own purposes. The turbofans will effectively generate thrust to achieve the high cruising speed while the large rotors will allow for effective VTOL operations with reduced downwash. However, an issue that is introduced with the separation of horizontal and vertical propulsion systems is that they can interfere with each others' operations. For example, during cruise flight, the tilt-rotor's rotor blades will create a large amount of drag while contributing nothing to propulsion. During VTOL operations, the turbofans, which will remain powered on, will produce forward motion while the aircraft is expected to hover in place.

The solution for this is to "disable" one of the propulsion systems when the other is being used. In cruise flight, the rotor blades can be folded back against the tilt-rotor nacelles, reducing the drag they generate. During VTOL mode, the thrust of the aft-mounted turbofans can be negated using thrust deflectors or a modified form of thrust reversers. It is necessary to negate the thrust rather than to stop and start the turbofans mid-flight because it may introduce issues having to go through engine startup procedures while flying.



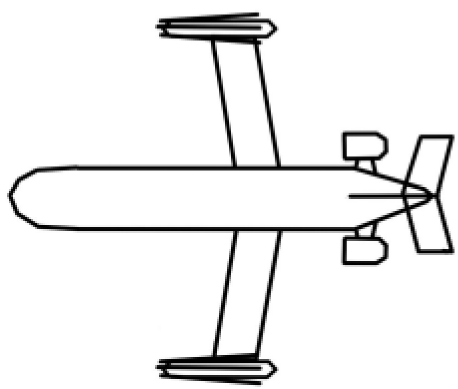
Cruise Flight Operation

VTOL Operation

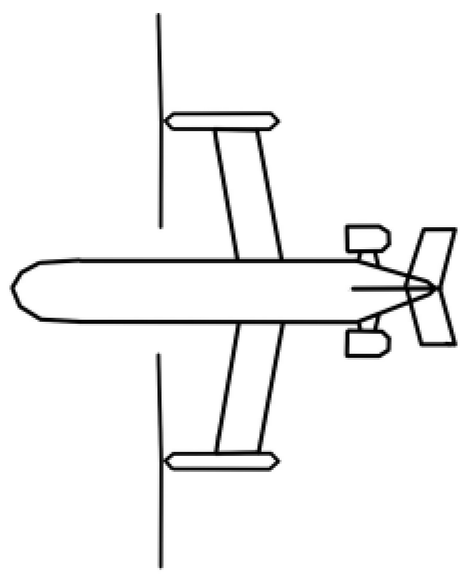
Additionally, it will be necessary for the turbofans to remain powered during VTOL operations because current battery technology does not allow the tilt-rotors to be powered solely through battery power alone. The turbofans will be connected to generators which power the tilt-rotors in conjunction with the batteries in order to produce the required power. During cruise conditions, when the tilt-rotors are not powered, then the generators will recharge the battery. By charging the battery mid-flight, it allows for a smaller battery to carry out the same mission parameters.

Multiple decisions had to be made for the lifting surfaces of the aircraft as well. For the wing, because of the high cruise speed approaching transonic speeds, it was determined that a swept wing should be used to reduce the wave drag. As such, we had to decide whether or not to use a back-swept wing or a forward-swept wing. A back-swept wing would be more stable than a forward swept wing, both structurally and aerodynamically. Despite this, the simple fact that tilt-rotor propellers would collide with a back-swept wing when tilting forward forced us to consider a forward-swept wing of 5°. A taper ratio of 1 was decided because the tilt-rotor nacelles need structural support on the wingtip.

For the empennage, we had to decide between a traditional horizontal stabilizer and a T-tail form. A traditional horizontal stabilizer would receive airflow even during high angles of attack while a T-tail would have its airflow disturbed by the wing below it. Additionally, a T-tail requires more structural support. However, a traditional horizontal stabilizer would interfere with the aft-mounted engines, so a T-tail configuration was superior in this situation. Because of the wing sweep and weight considerations, however, we are considering potentially looking at a V-tail design in the future.



Rotors Stowed



Rotors Deployed

With the wing and empennage of a traditional airplane, the control surfaces during cruise flight allow the aircraft to be controlled like a regular airplane. During VTOL operations, for ease of control, the only control will be provided through the tilt-rotors. The turbofans will have their thrust nullified so that only the rotors have an effect on the control. To control yaw, the rotors will tilt slightly in opposite directions, so the tiltrotors will be required to have a range of motion greater than 90°. Like a helicopter, pitch would be controlled through cyclic pitch control. The rotors will have to be counter-rotating to avoid having a torque imparted on the airframe that generates undesirable yaw, and since they need to both rotate at the same speed to achieve this, roll control will be provided by collective pitch control on either rotor. Because cyclic pitch control is required, collective pitch control can be implemented for no additional cost in complexity.

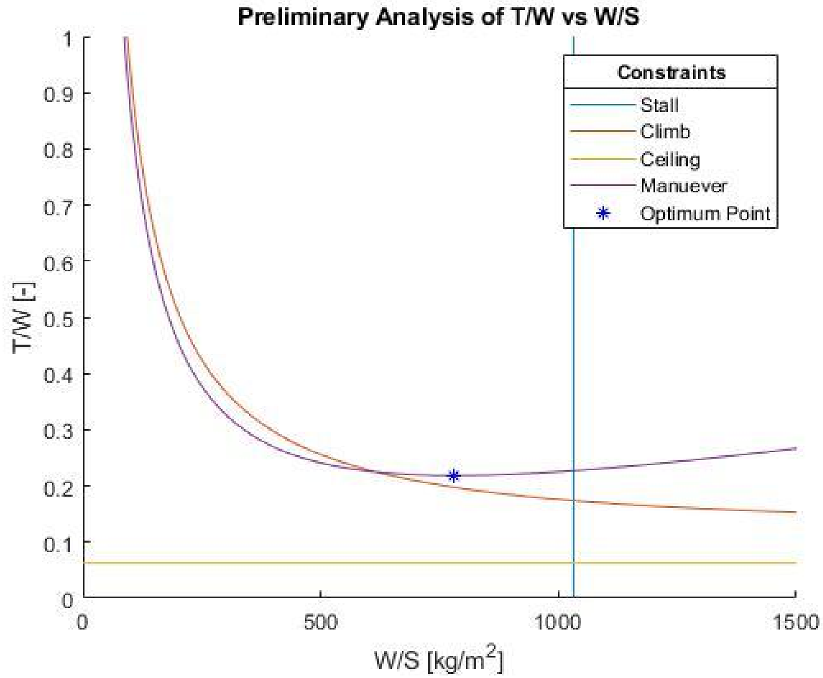
Sizing

For sizing we began by basing it off of the reference aircraft of the V-280 Valor and the V-22 Osprey. Although the V-280 Valor is closer in size and speed that we need, since the V-280 Valor is currently only in production, we can only get an empty weight fraction from its specifications. The V-22 Osprey gave us initial specifications for climb speed, stall speed, and was also used to compare our calculations for the crew weight, fuel weight and payload weight fractions. From this we made a sizing plot in Matlab using the various historical specifications and our requirements which gave us thrust loading and wing loading. We developed a Matlab code that used the requirements and the Breguet range equation to get a feasible fuel weight fraction then calculate takeoff weight, thrust needed and total mass of the fuel. Then it would calculate how much fuel we would need for flying at that thrust for the length of our total mission. Then we would take that value and use it as a new fuel weight fraction then repeat the process until our value that we put in and the value we got out made sense. Our final values compare well to the V-22 Osprey. Weight fractions, wing loading and thrust loading are given below in this table. The sizing plot is given below which is what gives thrust and weight loading.

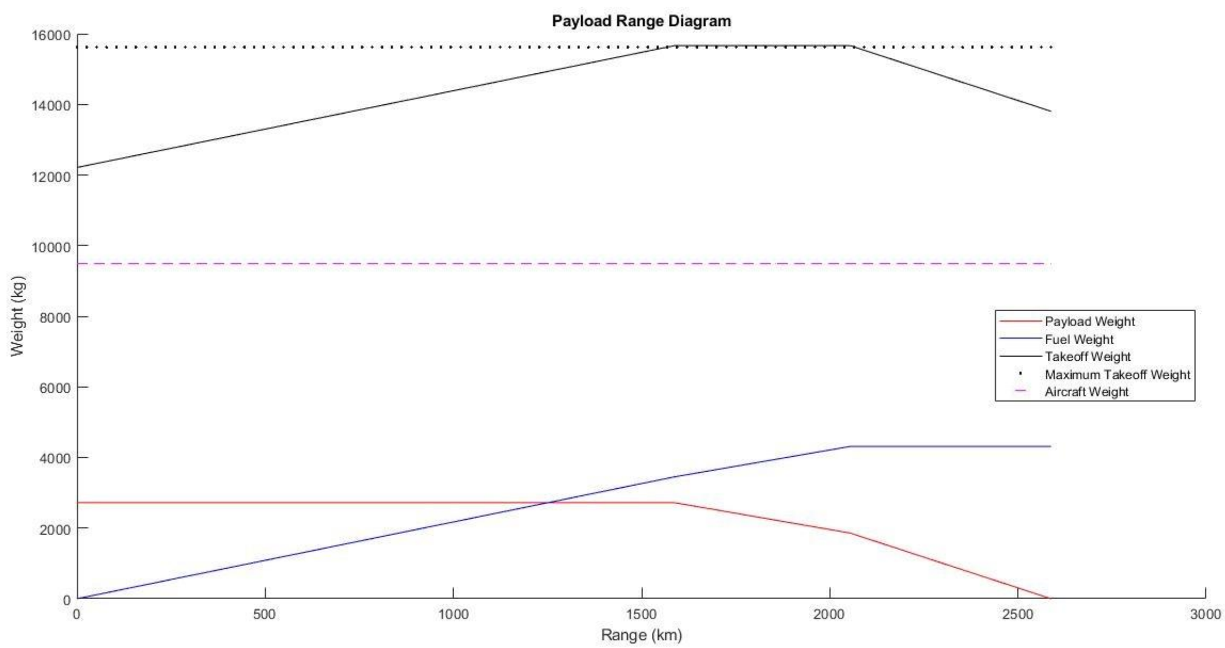
Sizing

Takeoff Weight	15622 kg
Empty Weight Fraction	0.5929
Fuel Weight Fraction	0.2183
Crew Weight Fraction	0.0201
Payload Weight Fraction	0.1679
Thrust Loading (T/W)	0.2188
Weight Loading (W/S)	780

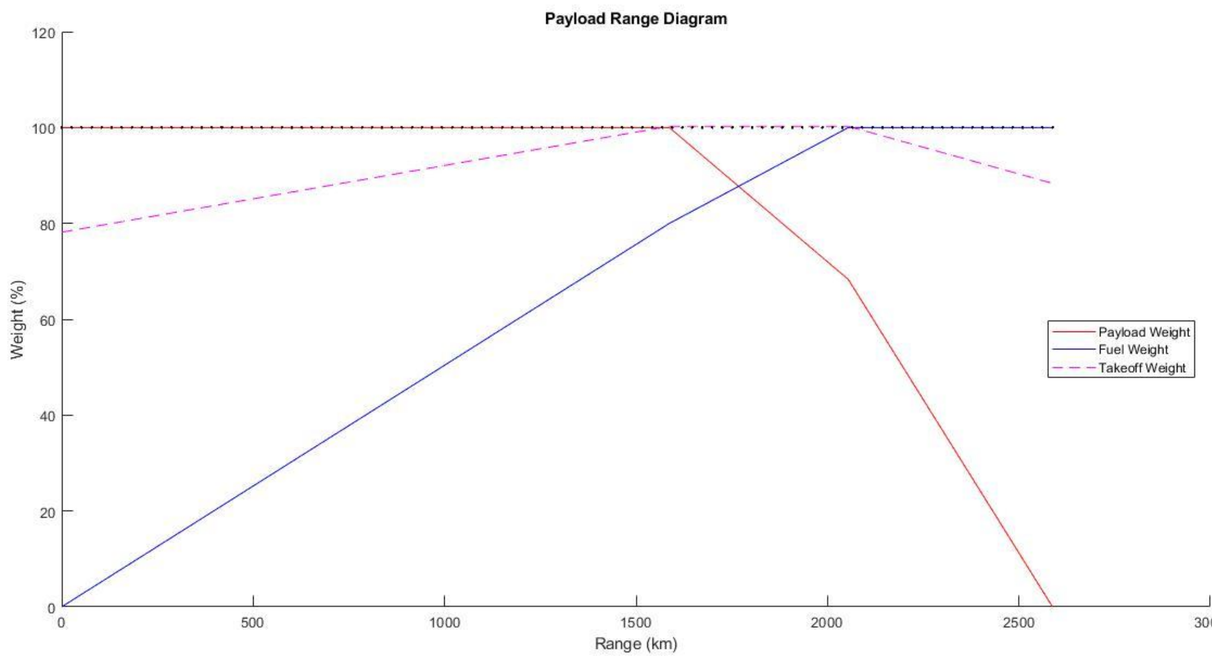
Sizing Plot



Payload Range Diagram



As the above diagram shows, the aircraft is capable of flying the full range specified by the VFS competition with the full payload specified. The fuel tank has 25% more capacity than a full mission requires. As the fuel increases beyond that amount, the payload weight must decrease in order to keep the take-off weight from exceeding the maximum take-off weight. Once the fuel tank is at full capacity, no more fuel can be added, but the range can still be extended by decreasing the weight of the payload, yielding a lighter aircraft and thus further range.

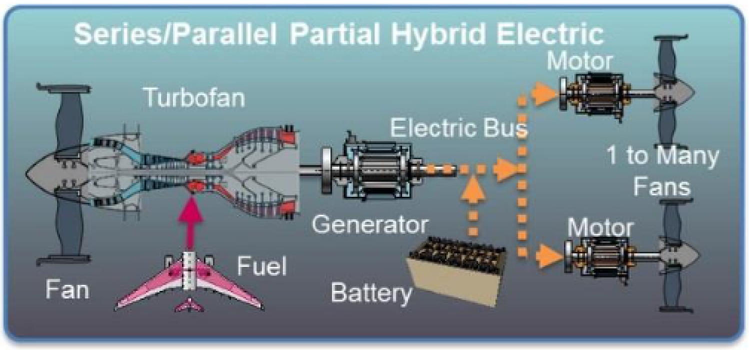


The payload range diagram above shows this dynamic as a percentage of its maximum weight rather than total weight. As can be seen, there is a tradeoff between payload weight and range once the fuel reaches the point where the full payload can be carried its required range. This shows that despite the rated range of the aircraft, it applies to the full payload capacity, and the aircraft can actually travel significantly further if one decreases the payload carried onboard.

Propulsion

Our configuration is a partial hybrid electric system. The reason that the electric tilt-rotors are powered with both battery and a generator in conjunction is because a battery-alone system would have a prohibitively heavy battery. A generator-only system would be unable to provide the energy required to provide enough lift for the VTOL operation, so a partial-hybrid system was chosen, taking energy from both a generator and battery.

Propulsion System Diagram

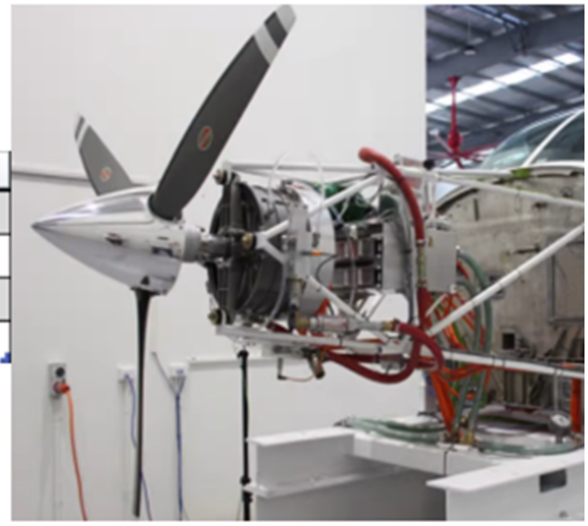


For our engines we chose to mount two PW306b turbofans on the rear of the plane. According to our calculations we need a maximum thrust of approximately 19.16 kN per engine in order to reach the goal speed of 833 km/hour. The PW306b turbofans more than accommodate our needs with a maximum thrust of 21.13 kN each. We chose a turbofan over other options because of the lower fuel consumption when compared to a turbojet, the lack of feasibility of a propeller plane working at a height of over 6000 meters, and we approach but to not cross into the area of transonic speed with a Mach number of 0.7320 at cruise. Below is some relevant information on the PW306b turbofan.

PW306B Turbofan	Value
Overall Length	1888 mm
Overall Height	1138 mm
Overall	965.2 mm
Overall Diameter	1138mm
Thrust, Maximum Continuous	26910 N
Interturbine Temperature Contineuous	920 C
Low Pressure Rotor N1 rpm	11138 rpm
High Pressure Rotor N2 rpm	28277 rpm
Cruise Thrust	5,030 N

The electric motors required power output and the battery density required to store the power are not realistic with today's technology. Our goal was to design the plane of tomorrow, not today, and therefore our conceptual design was based on technology that we assume to present in the early 2040s. We need a battery density increase from the present day maximum of around 170 kW/kg to a value of 700 kW/kg in order to mitigate the weight of the battery. We also need a power output of 2500-2800 kW per motor (assuming only two motors). The Magni650 is one of the best electric motors suited for flight on the market today and back in May of 2020, was able to power the largest electric aircraft to ever take flight, a modified Cessna Grand Caravan 208B. This motor however, only has 640 kW of power, about a fourth of what is required in order to achieve proper EVTOL. Therefore with an assumption of a 9% increase in power output and battery density year over year we can see that it is possible to create this aircraft in the year 2040 with a power output 2769 kW and a battery density of 735 kW/kg.

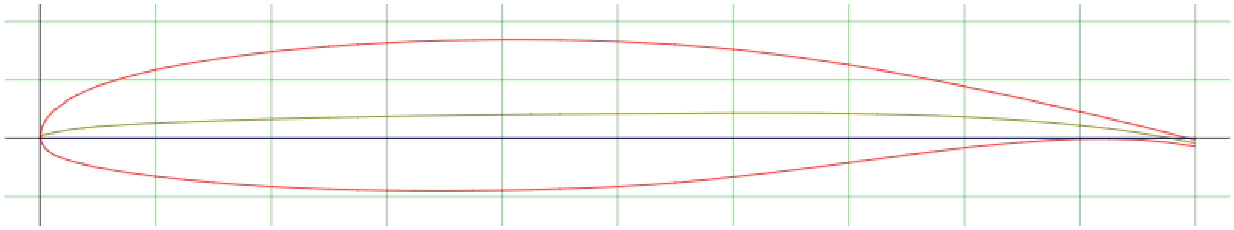
Description	Value	Neede
Motor Type	Electric	N/A
Power	640 kW	2500 kW
Torque	2820-3020 Nm	TBD
Weight	200 kg	TBD

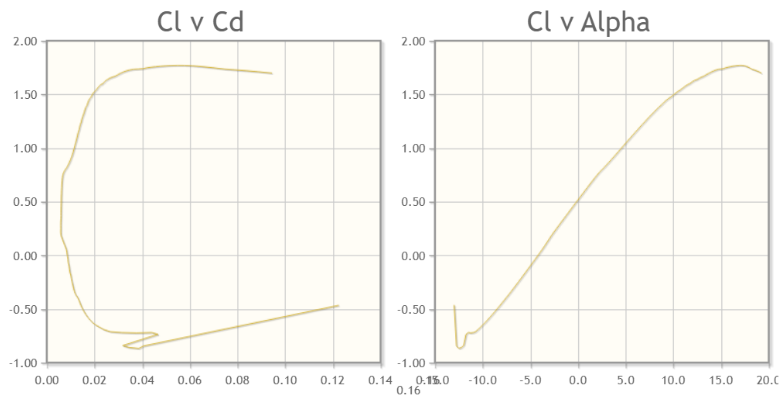


Aerodynamics

For our airfoil we decided to go with the Nasa/Langley LS(1)-0413 because it meets the requirements for our sizing parameters and aerodynamics. We needed an airfoil that can produce a lift to drag ratio of at least 16. If you look at the polar drag chart displayed below we can easily achieve that cl/cd ratio. We also wanted to pick an airfoil that is thick enough to carry the fuel we need for our flight and also be structurally stable. However our aircraft also travels at high speeds and needs to have minimum drag during flight. Therefore we decided to make the airfoil thin enough so that the drag is optimal for cruise flight, but thick enough to carry our fuel. After our PDR presentation the professor pointed out that this airfoil would not perform well in transonic flow and therefore we will change our airfoil and pick a supercritical airfoil to meet our specs for transonic flow. However we would still like to find an airfoil that produces similar L/D ratios and also similar thickness.

We added a twist angle of 3 degrees from root to tip so that the wing stalls at the root first. We decided on a taper ratio of one because we want there to be room on the root tip of the plane for the propellers and motors to mount. We also decided on a forward sweep angle of 5 degrees so that we can minimize the onset of wave drag and also allow for our propellers to work without interfering with the planform. After our PDR presentation professor Hwang pointed out that this forward sweep might be problematic and not actually reduce wave drag. We will further research on this topic to see if forward swept wings are feasible.





Using the equations in the class and in the textbook and our airfoil's values, we were able to calculate these aerodynamic coefficients. These represent the aerodynamic coefficients of the aircraft as a whole (during cruise flight). These calculations gave us the values we needed to design the geometry of the plane, such as the wingspan. It also gave us the location of various aircraft components relative to each other and allowed us to position other aircraft components to appropriately place them, such as the landing gear and aft-mounted engines. For parasitic drag we decided to use the equivalent skin-friction method from the Daniel Raymer textbook for simplicity. Then all other equations were gathered from the class slides.

Aerodynamic Values

C_{D0}	0.0028
C_{Dw}	0.5929
C_D	0.2183
$C_{L,cruise}$	0.3435
L/D	20.4934
AR	7
Span	13.64 m

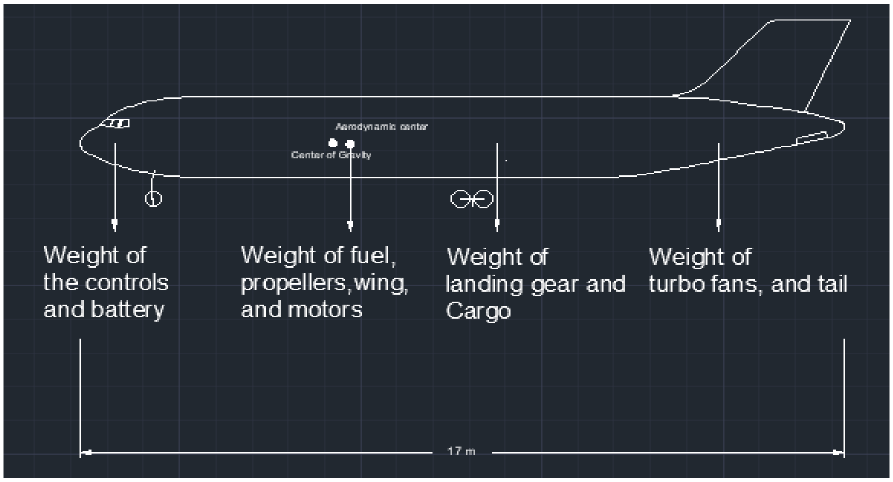
X_{cg}	8.3151 m (9 % of the chord)
X_{np}	8.5713 m (22 % of chord)
Static Margin	13.15%

Weights

Our team calculated values for our weights directly from the equations in class and also based some of our weights off of the V22-osprey. The Osprey has a very similar fuselage and wing design to what we are trying to achieve. However the V-22 is slightly larger in size than the aircraft that we are trying to design so therefore we scaled down the weight of the fuselage and wings to be proportional with the osprey. The payload and cargo were given to us by the VFS competition specs. The fuel weight was calculated based on the range of the aircraft and thrust produced by the turbofans. The battery weight is proportional to the power needed for VTOL and also the altitude we need to rise. The weight of the landing gear and Electronics were based off of other aircrafts that did similar VTOL maneuvers. We included fudge factors for most of the components of the plane to reach the gross weight that we calculated in our sizing. We are assuming that this aircraft is to be released in the mid 2040's which means that the technology and material properties will have improved for aircrafts. The fudge factor for our fuselage is a bit low and we are trying to increase that value so that it is more reasonable.

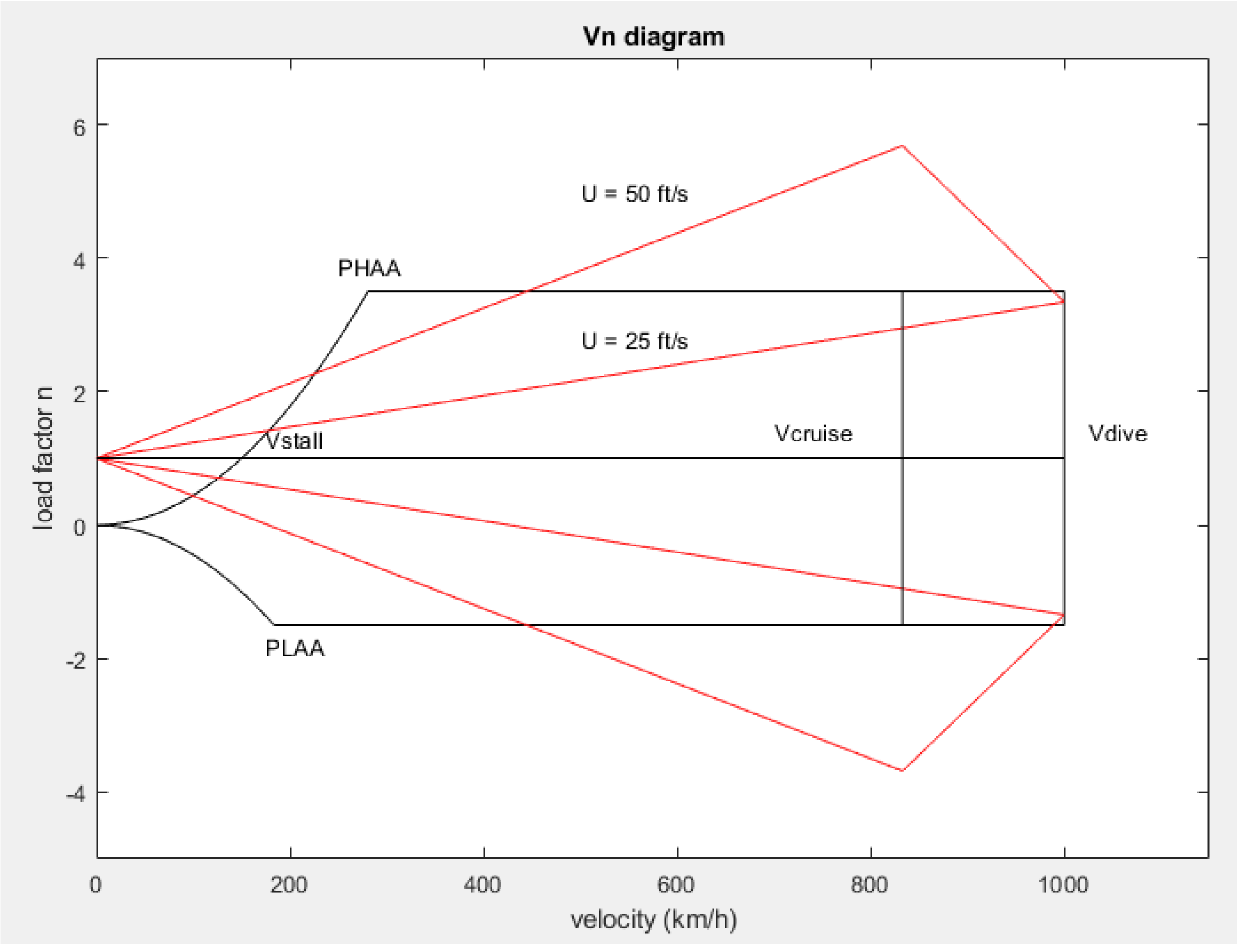
We next estimated the location that the weights of the different parts would be acting at along the fuselage. From this we were able to calculate the center of gravity of the entire aircraft. We approximated this value to be at the location 8.33 meters from the front of the fuselage. We then positioned the wing slightly behind the center of gravity location at x = 9 meters. This is so that the plane remains stable during flight. If there was ever any pitch up moment the lift at the aerodynamic center would counter that change in angle of attack.

Part	Weight (kg)	Moment Arm (m)	Fudge Factor
Payload + Cargo	3060.19	12.07	None
Wings	1507	7	0.75
Tail	907.19	16.5	0.7
Fuselage	8870	8.5	0.6
Fuel	3534	8	None
Battery	500	1	None
Landing Gear	1313	10	0.7
Electronics and Propellors	1000	6.5	0.7



V-n Diagram

We calculated the load factors of our aircraft relative to our velocity on the Vn diagram. The max load factor for maneuvering was given to us from the VFS competition guidelines. The minimum load factor was estimated to be -1.5 based on the structural strength of the wings and aircraft. The stall velocity was calculated from our Clmax, which is given above in the aerodynamics section, the wing area, and dynamic pressure. The cruise velocity was given to us in the competition guidelines. The Vdive was estimated based on when we determined our wings will fail from flutter. The load factors from wind gusts were calculated in the vn diagram and you can see the estimated values in the red envelope. This gust envelope accounts for winds of 25 ft/s and 50 ft/s.



Future Work

So far, we have spent a lot of time working on the aircraft as it behaves in cruise mode. More thought and analysis needs to be put into discussing the aircraft as it is in VTOL mode, when it is relying on the electric tilt-rotors for its operation. The amount of rotor blades, the blade properties and geometry, and its speed need to be determined confidently. Additionally, we need to find the optimal ratio of battery power–to–generator power to power the tilt-rotors most efficiently. There are also optimizations that can be made in regards to stability and the airfoil.

Overall, the fuel capacity and battery capacity need to be optimized to yield the greatest performance with the least fuel and battery weight. The airfoil geometry can be optimized to meet all requirements while maintaining good performance, and the wing shape can be further optimized in terms of sweep angle and size. Afterwards, the weights and positions of various components such as the motors, engines, and landing gear can be determined to give the proper weights and balances.

The estimation of future technology and its influence on the aircraft design can be further refined to give more realistic expectations and estimates.

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