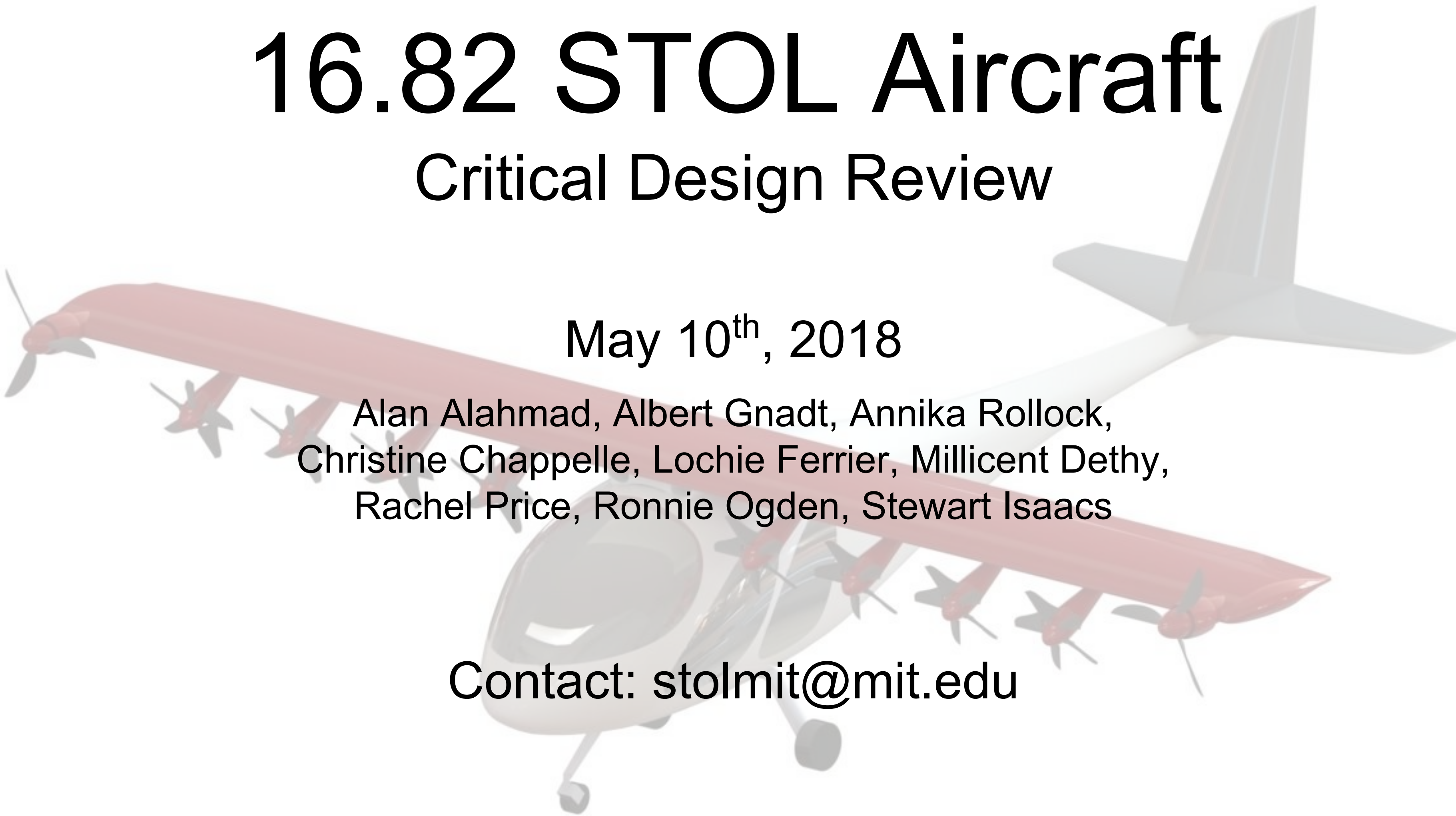
16.82 STOL Aircraft

Critical Design Review



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Outline

1. Motivation
2. General Overview
3. Sizing
4. Configuration
5. Subsystems
6. Performance
7. Risk
8. Conclusion

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UAM Market is Booming

- UAM: urban air mobility
- On-demand mobility has emerged for ground transportation (e.g. Uber)
- Outside of urban cores airport infrastructure is widespread and underutilized
- Potentially a new operating market

Current Solution for UAM is eVTOL

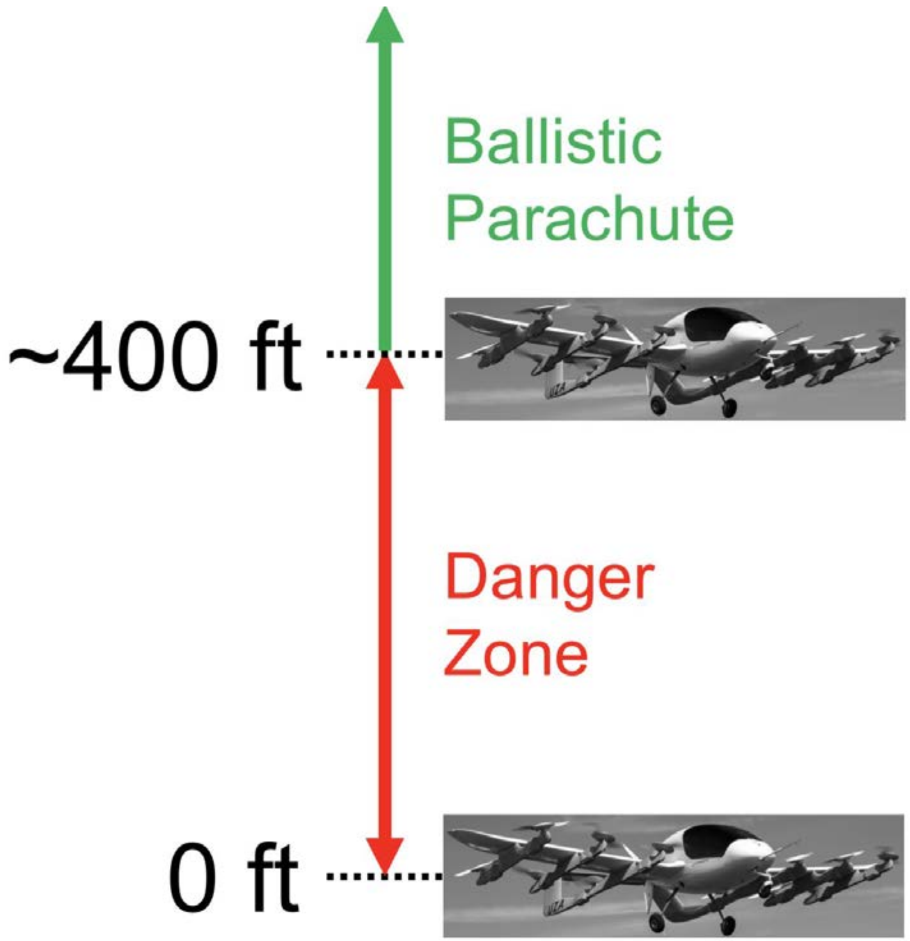
- eVTOL: electric vertical takeoff and landing
- eVTOL initiative driven by Uber Elevate

Current Solution for UAM is eVTOL

- 50+ projects underway, many configurations

eVTOL Aircraft Present Certification Challenges

- Reliance on electrical power system
- Low altitude hover power failure risk
- Fly by wire control system required



STOL Aircraft Offer an Alternative

- STOL: short takeoff and landing
- May be able to operate in similar takeoff and landing footprints as eVTOL
- **Lower certification risk than eVTOL**
  - Glide capable, stall speed < 61 kts
  - No critical loss of control
- More efficient in cruise
  - Avoid drag and mass of vertical lift system
  - Increased range and/or payload

Objective

4-passenger STOL vehicle capable of takeoff and landing on 300 ft runways **or less** to compete with eVTOL designs.

High-Level Requirements

Specification	Minimum Requirement	Design Point
Payload (includes pilot)	4 passengers and baggage	(205 lb + 20 lb) x 4 passengers = 900 lb total payload
Payload Volume	Able to accommodate medical litter or skis	84" x 24" floor area available in cabin
Range	100 nmi with reserves	100 nmi with 30 min reserve at endurance speed (94 kt)
Speed	120 kt cruise minimum	120 kt
Runway	300 ft maximum (214 ft with FoS) 400 ft over 50 ft obstacle (286 ft)	100 ft maximum (71 ft with FoS) 143 ft over 50 ft obstacle (286 ft)
Crosswind Capability	20 kt	20 kt
Weather	IFR Capable	IFR Capable

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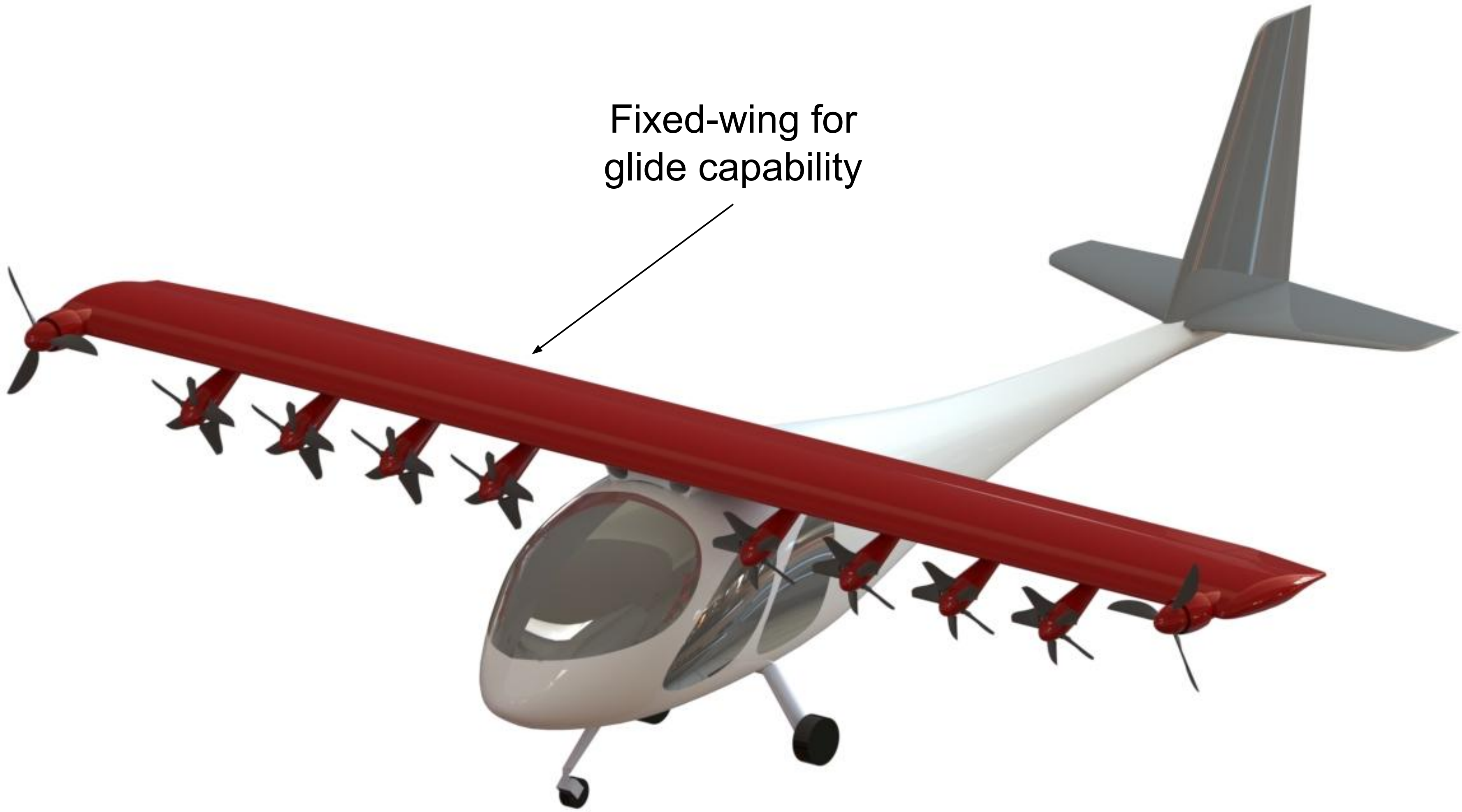
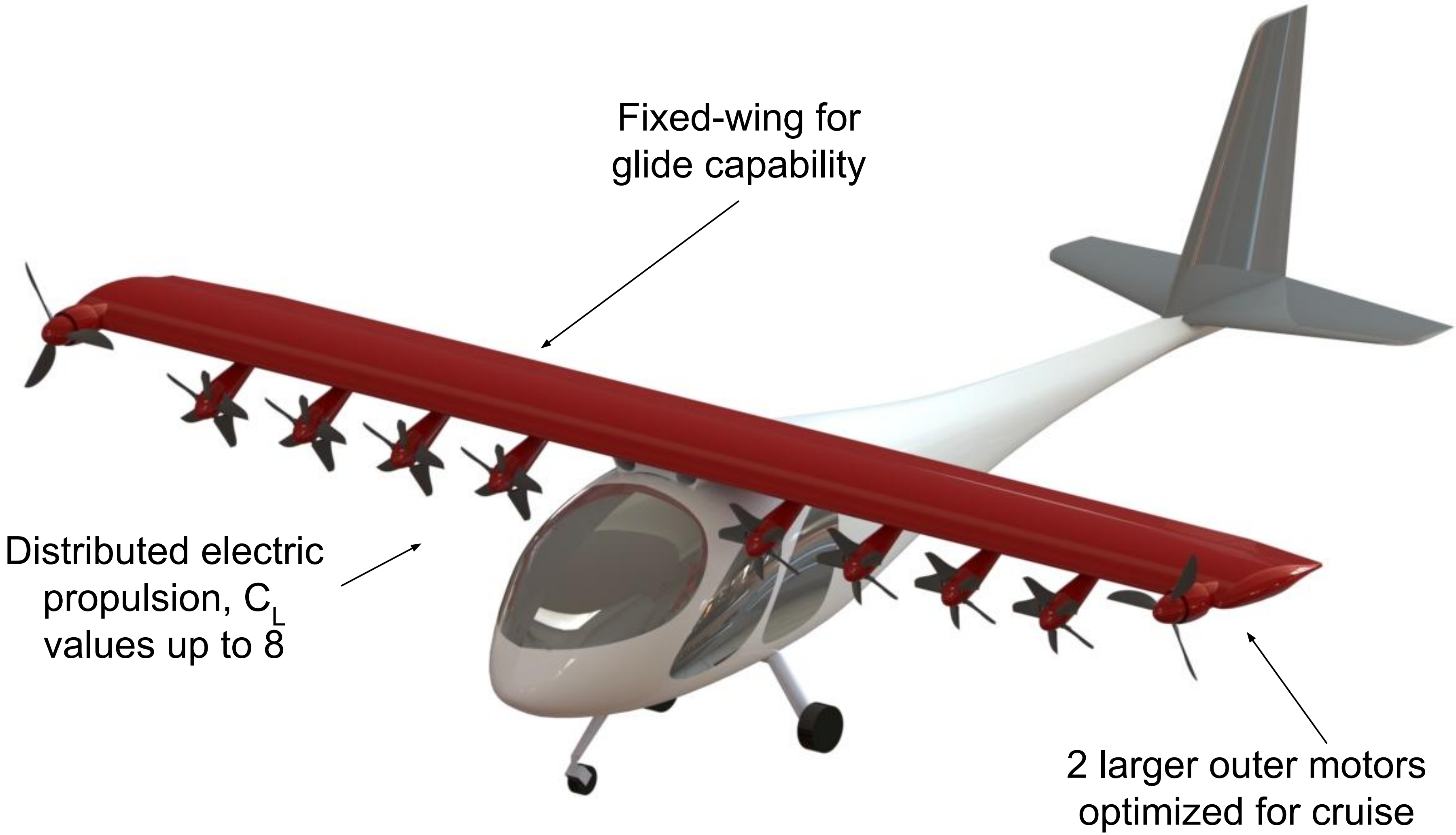
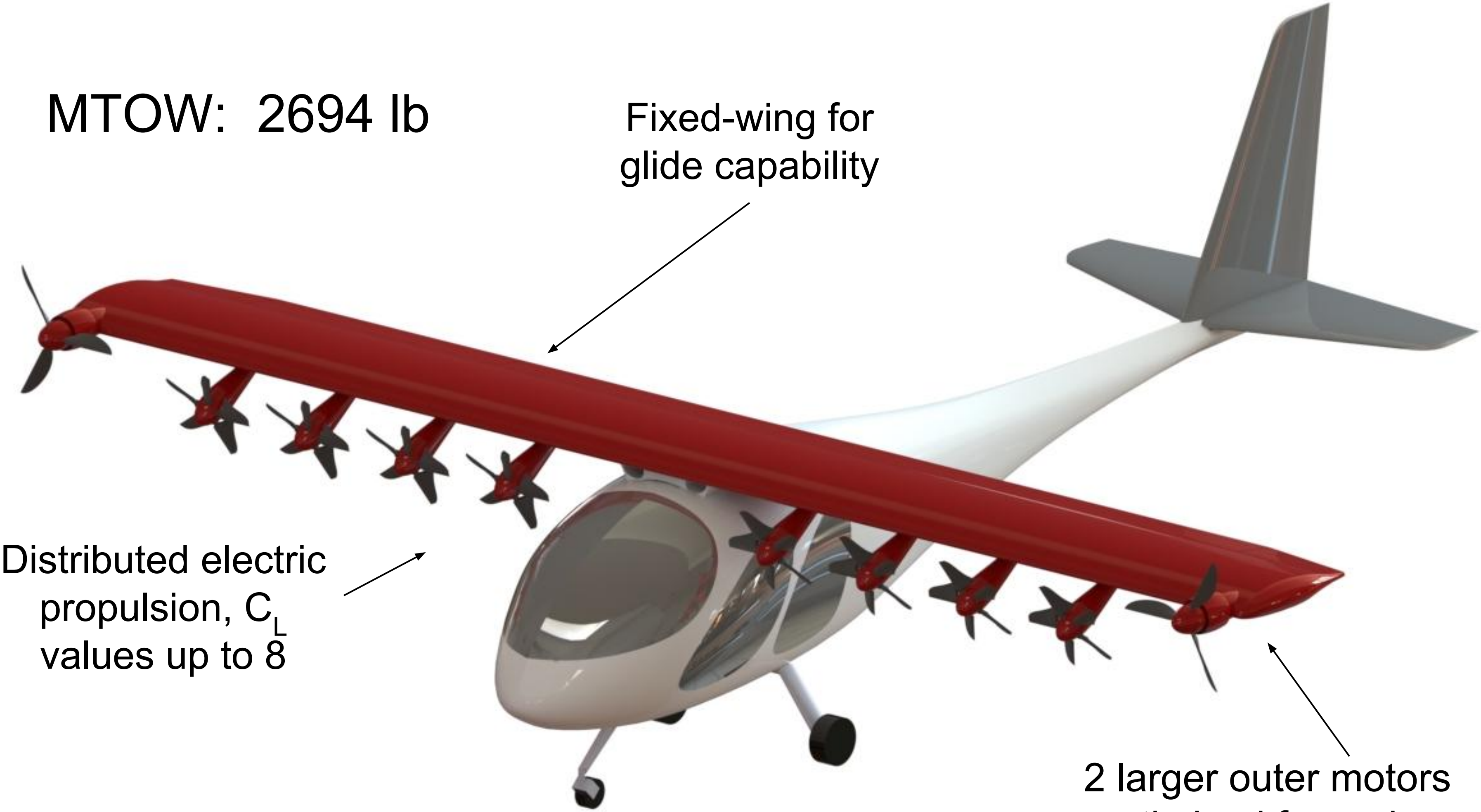
Key Features


Fixed-wing for
glide capability


Fixed-wing for glide capability
Distributed electric propulsion, C_L values up to 8
2 larger outer motors optimized for cruise

MTOW: 2694 lb



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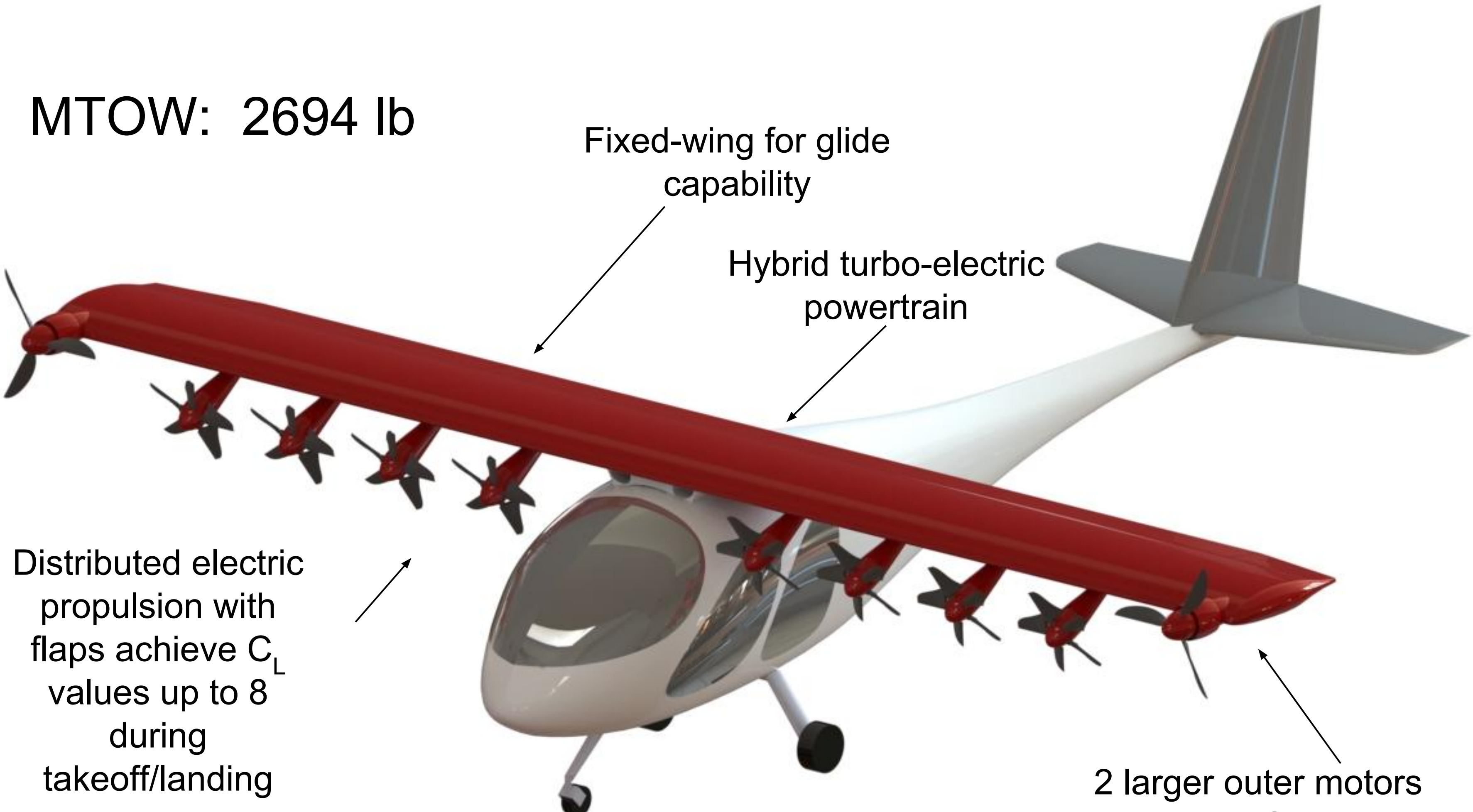
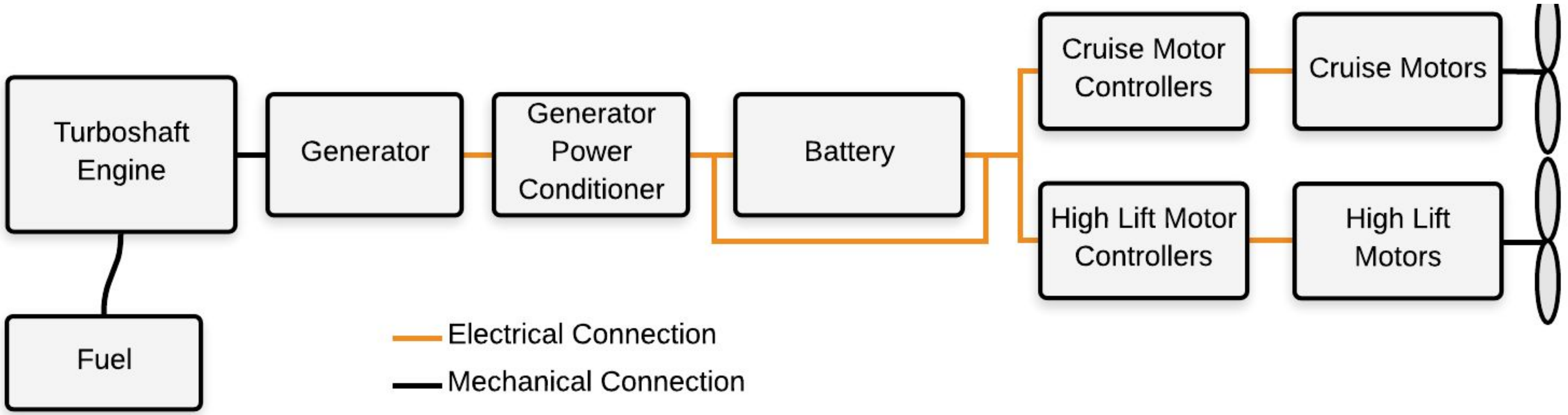

Fixed-wing for glide capability
Hybrid turbo-electric powertrain
Distributed electric propulsion with flaps achieve C_L values up to 8 during takeoff/landing
2 larger outer motors optimized for cruise

Hybrid Turbo-Electric Powertrain

- Maximize blown-slotted lift with distributed electric propulsion and meet range requirements with less battery weight
- Batteries enable high power burst for takeoff, obstacle clearance, and landing
- In-flight battery charging minimizes aircraft turnaround time, ground infrastructure
- 2 battery options: Li-ion & NiMH



Blown Slotted Flap

- Achieve C_L values of 8 and X for takeoff and landing respectively
- Potential weight reduction due to distributed wing loading
- Flap deflection further increases C_L

Operations

Operating Missions

Urban

- Aircraft will perform short missions across the city (landing on STOLports)
- Refueling will occur at STOLports

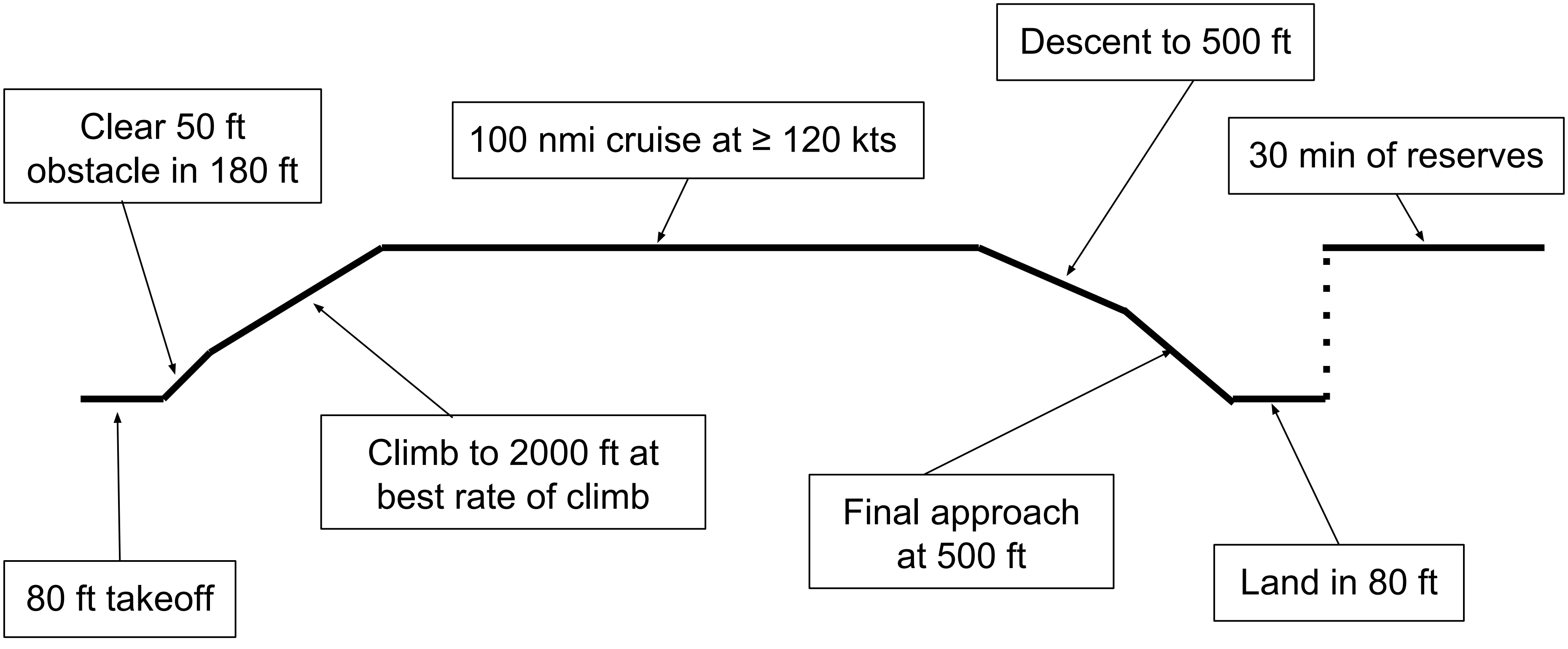
Backcountry

- Aircraft takeoffs and lands in the bush

Medevac

- Occur in both the city and for rescue missions in the bush

Generic Mission Profile



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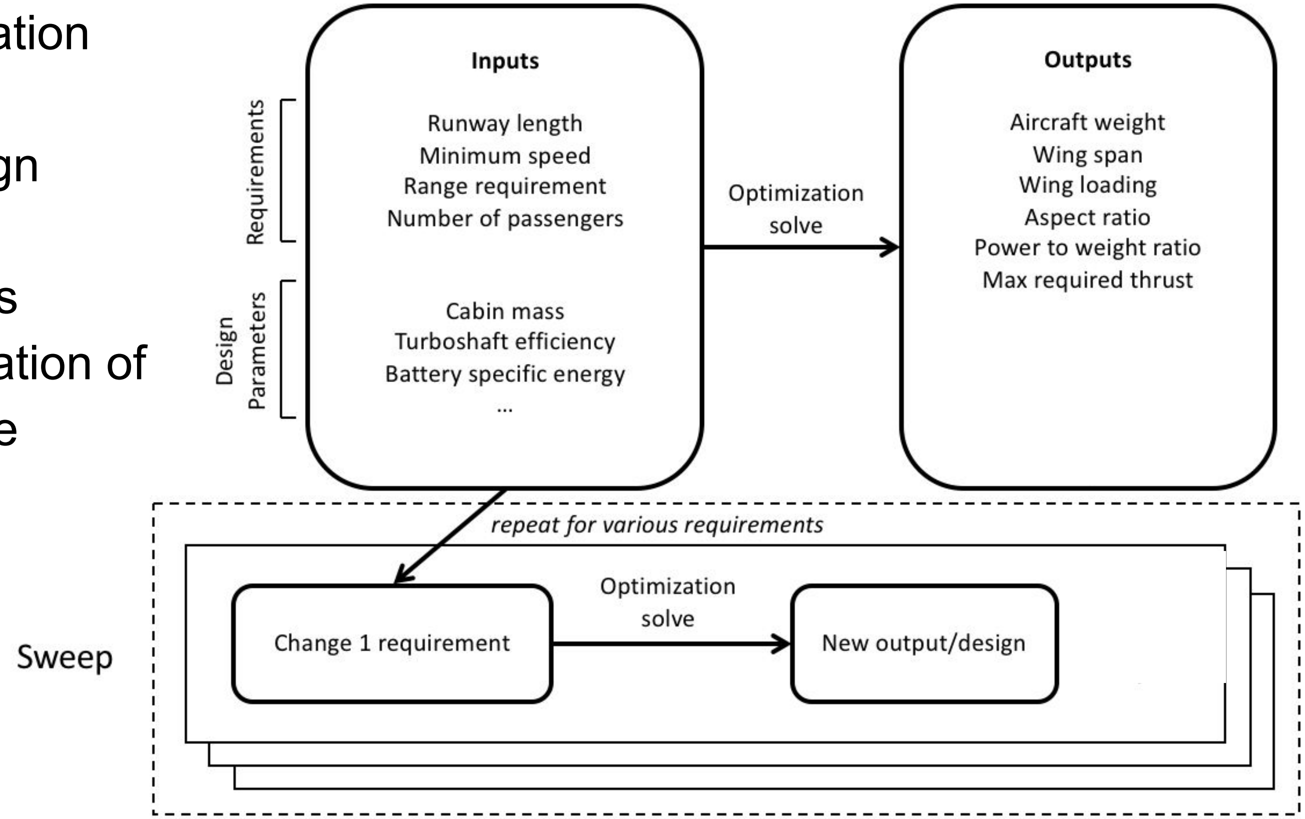
Modeling Assumptions

GPkit Introduction

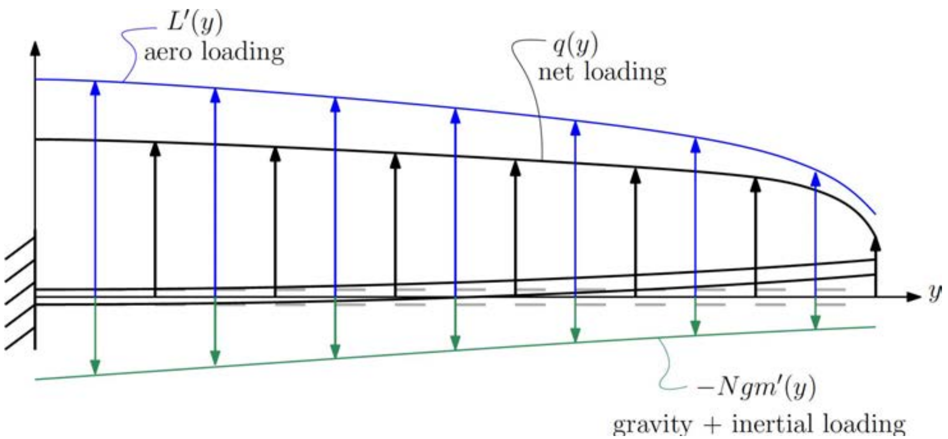
- Uses convex optimization for:
  - Conceptual design
  - First principles equations/models
- Allows for fast exploration of unfamiliar trade space

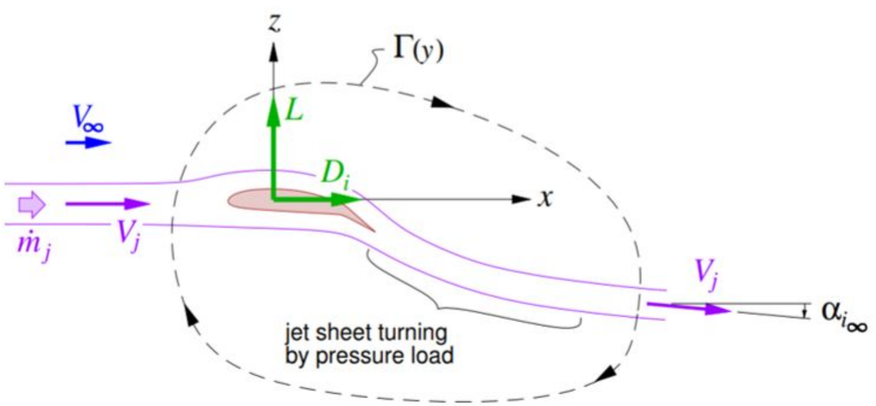


GPkit Vehicle Assumptions

Blown Wing Model

- Mark Drela's Blown Wing Model
  - Assumes even jet height, uniform blowing and uses actuator disk theory to calculate propulsor performance





GPkit Vehicle Assumptions

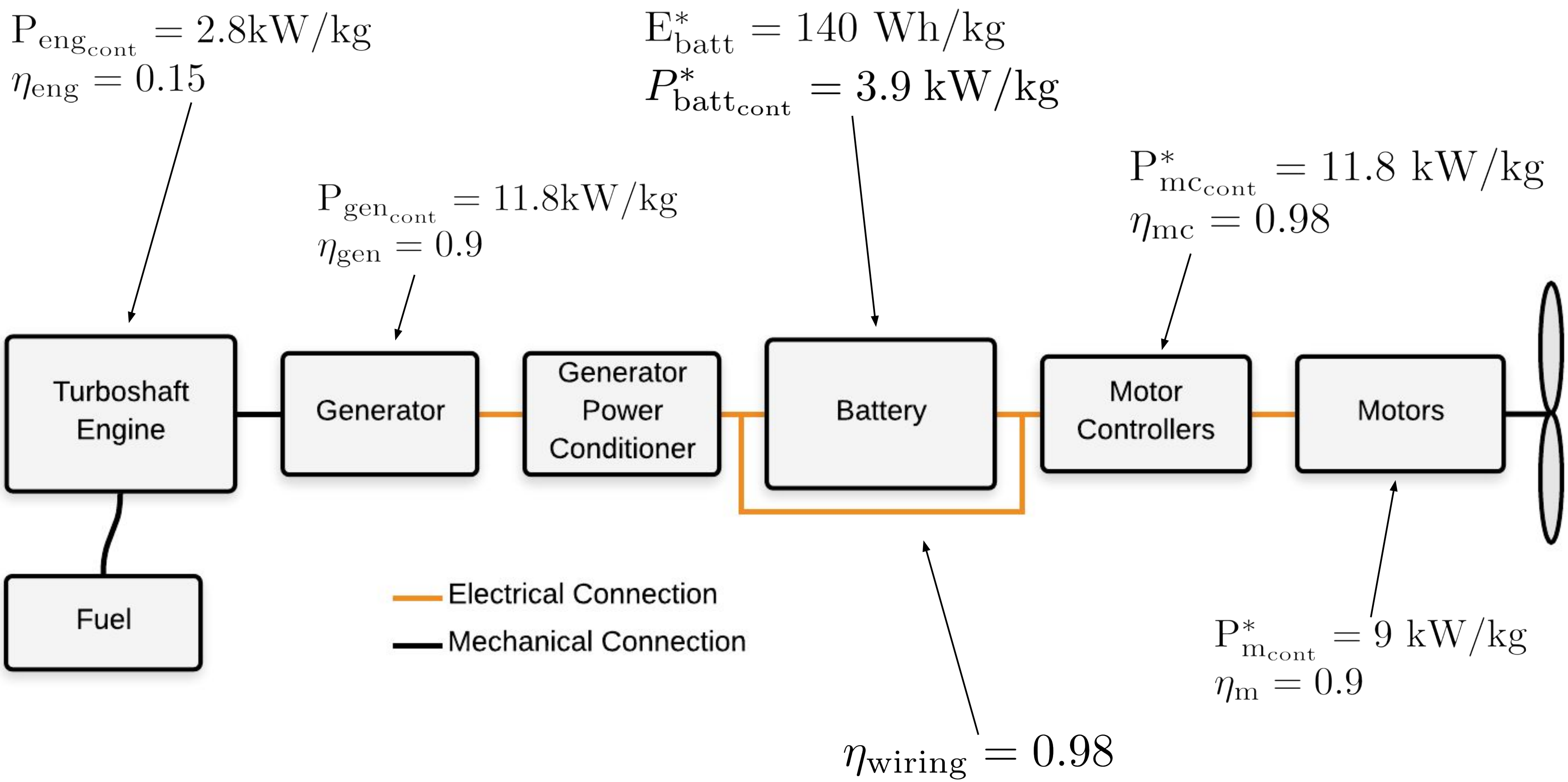
Wing Structural Model

- Constant width and height cap spar
- 5 carbon ply skin
- No bending relief

Tail Structural Model

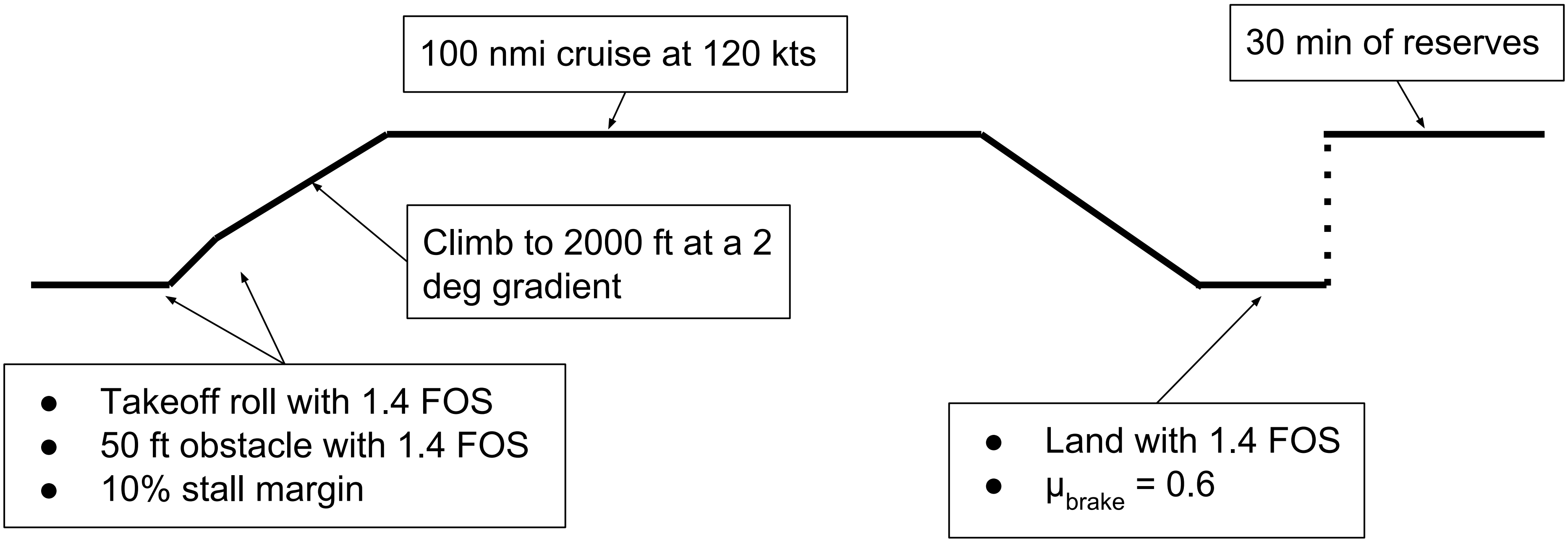
- Constant diameter carbon boom sized by max tail load, with friction drag
- 2 ply carbon skinned tail surfaces

GPkit Powertrain Assumptions



GPkit Mission Assumptions

- Mission executed assuming **900 lb total payload** (4 passengers with baggage)
- Assumes no vehicle weight change during flight (<10 % fuel mass fraction)
- Battery used only during takeoff, obstacle climb, and landing



GPkit Vehicle Assumptions

Fuselage and Cabin Model

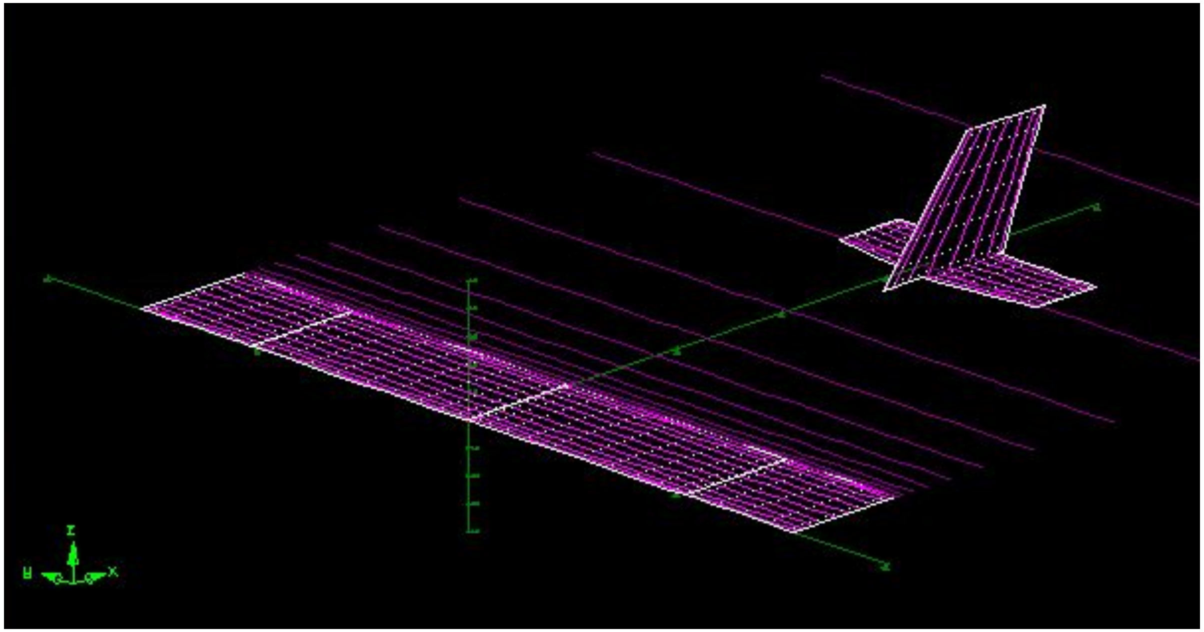
- Fixed equipment mass of 317 lb (gear, seats, avionics, etc)
- Fixed fuselage length, width, height, and wetted area

Other Assumptions

- 0.25 kW constant avionics power draw
- Propeller tip mach limit of 0.5
- Tail sizing (Vv, Vh) validated from JVL results

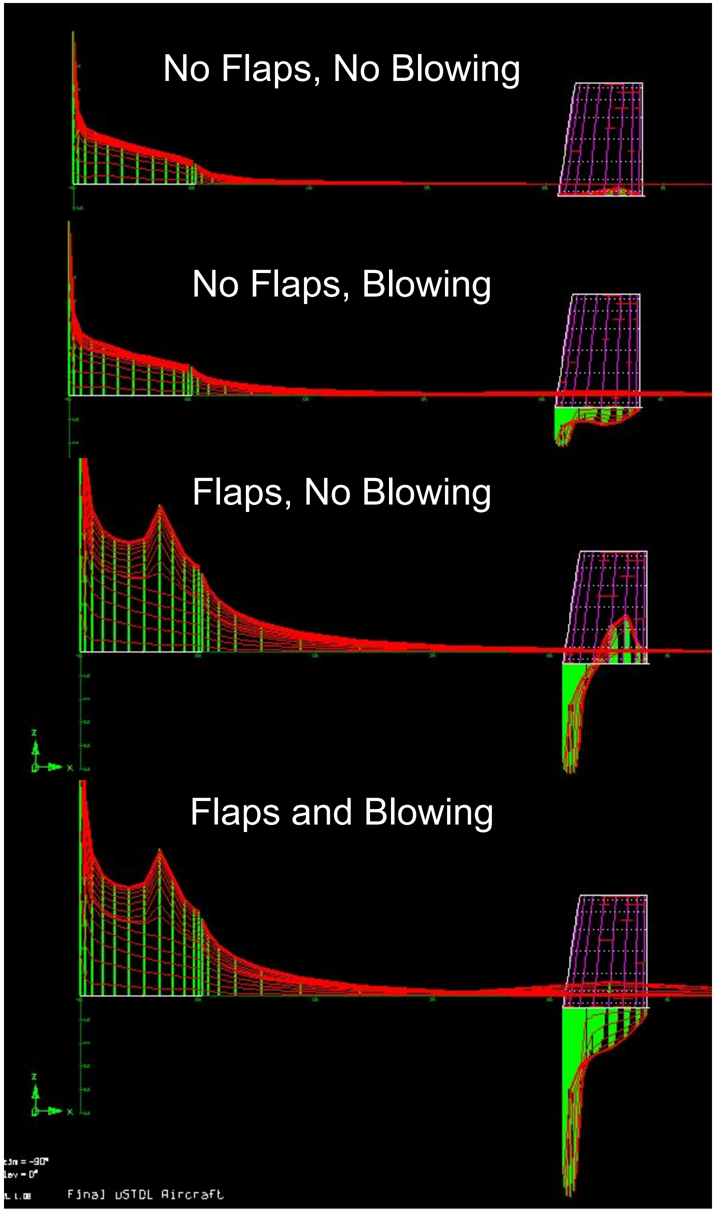
JVL Modelling

- JVL is vortex lattice code that accounts for jet sheet vorticity
- Use:
  - Tail sizing
  - Neutral point estimation
  - Verification of GPkit results



Blowing/Flap Effects

- Base case → added blowing: requires more up-trim
- Base case → added flaps: requires more down-trim
- Extreme blowing with little flap deflection or extreme flap deflection with little blowing requires large tail
- Blowing and flaps work to neutralize each other’s moment effects



JVL Tail Sizing

- GPkit's model chooses V_h based on most extreme combination of C_L and C_J
- GPkit assumes fixed V_v of 0.1
- Horizontal tail was sized for controllability during:
  - High power TO/Landing
  - Unblown TO/Landing
- Fin sized for:
  - Crosswind capability during hgh power landing
  - Engine-out unblown landing
- Automatic motor balancer assists in event of lost engine

GPkit Model

The full GPkit model is open-source and available on GitHub.

https://github.com/convexengineering/1682stol

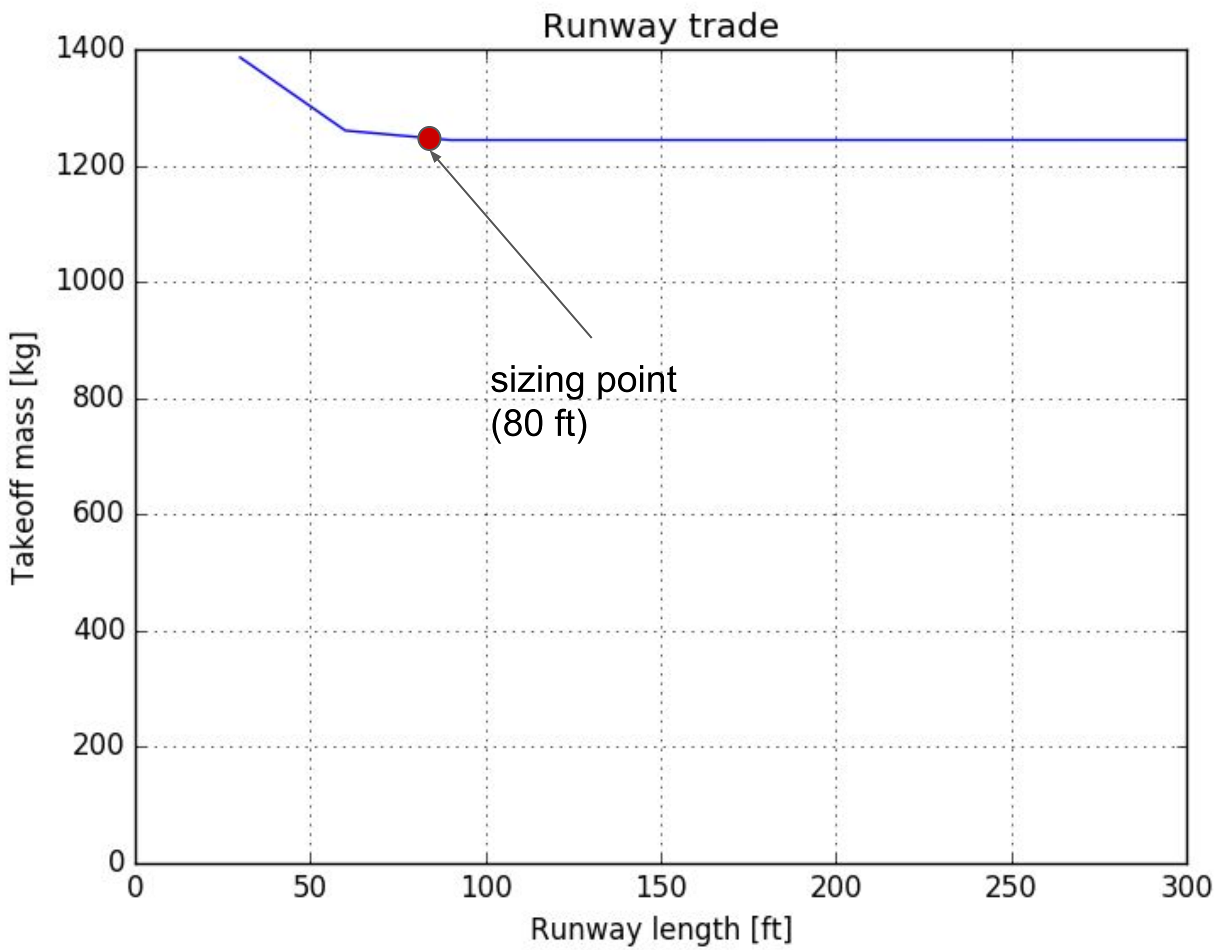
GPkit Optimization Setup

Minimize(mass) (mass is usually proportional to cost and complexity)

100 nmi range, 120 kt cruise and 900 lb payload case

$L_{obstacle} = L_{runway} + 100$ ft

GPkit Runway Sweep



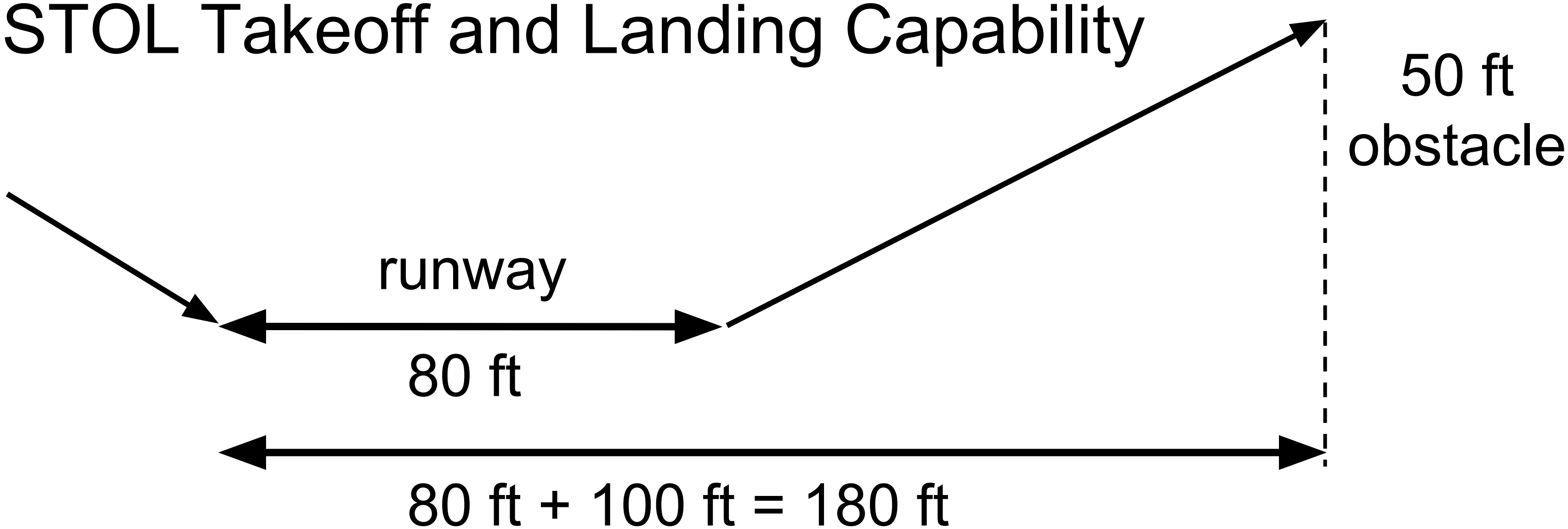
GPkit Runway Result

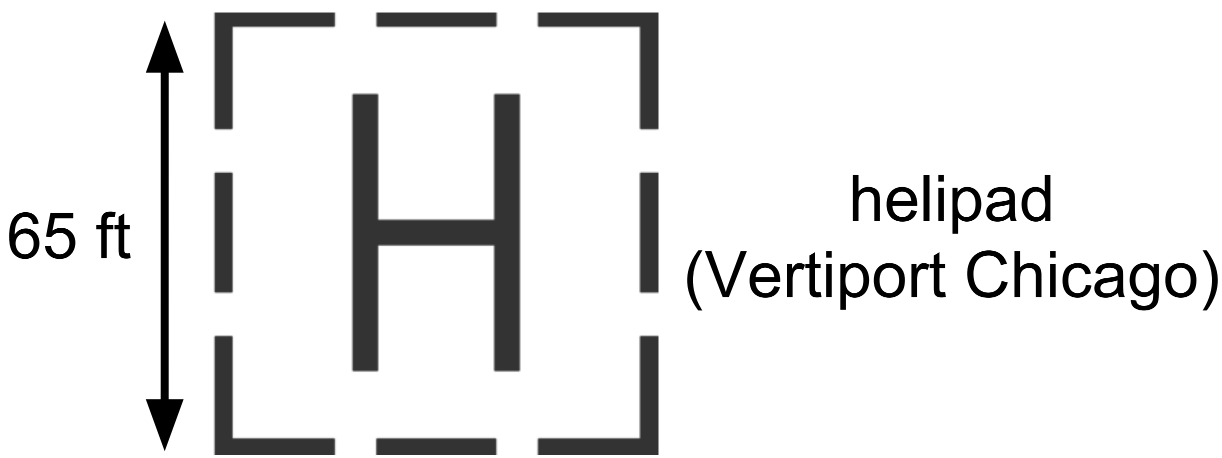
- **80 ft runway length with 40% margin (57 ft groundroll)**
- 180 ft length for 50 ft obstacle with 40% margin

For context:

- **US basketball court is 94 ft long**
- Typical helipad is 65x65 ft (Vertiport Chicago)

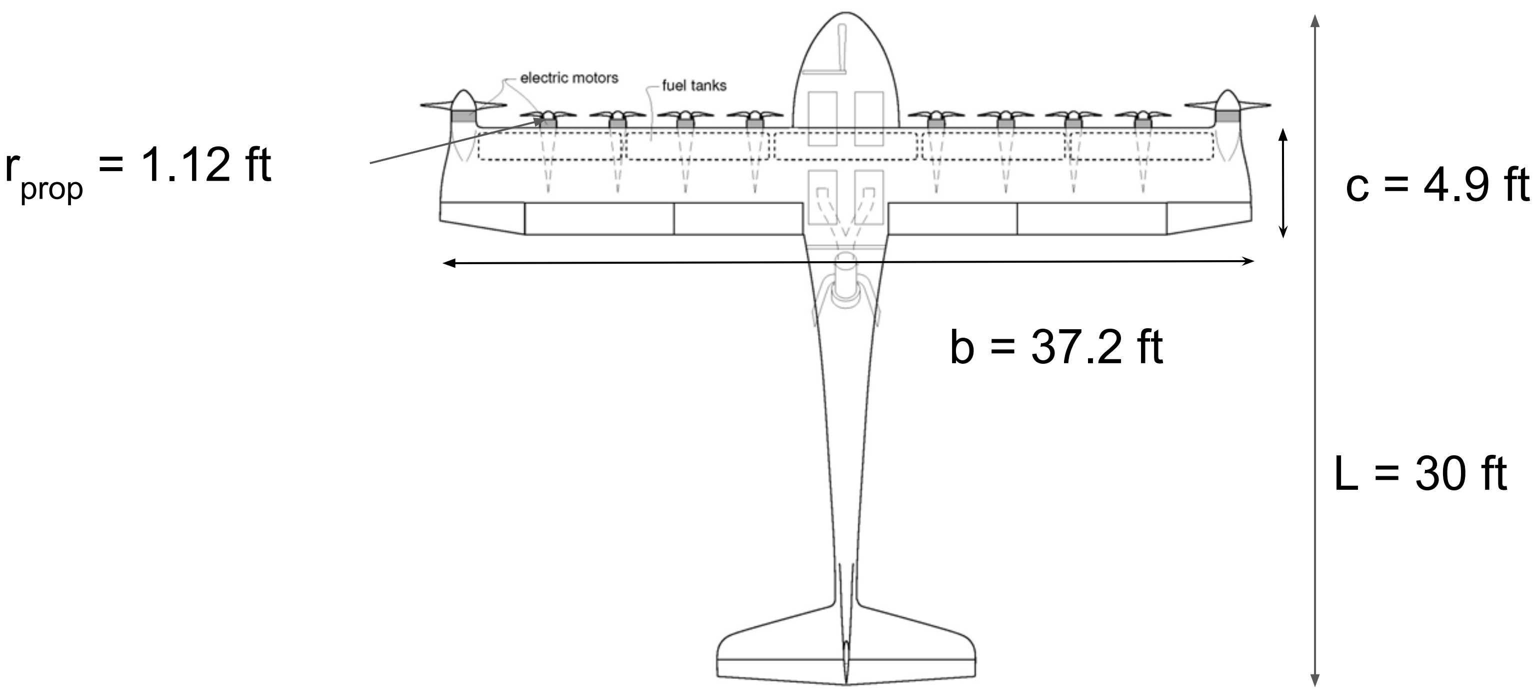
STOL Takeoff and Landing Capability





GPkit Vehicle Key Sizing Results

MTOW	= 2694 lb	(1222 kg)
Battery	= 130 lb	(59 kg)
Fuel	= 131 lb	(20 gal, 59 kg)



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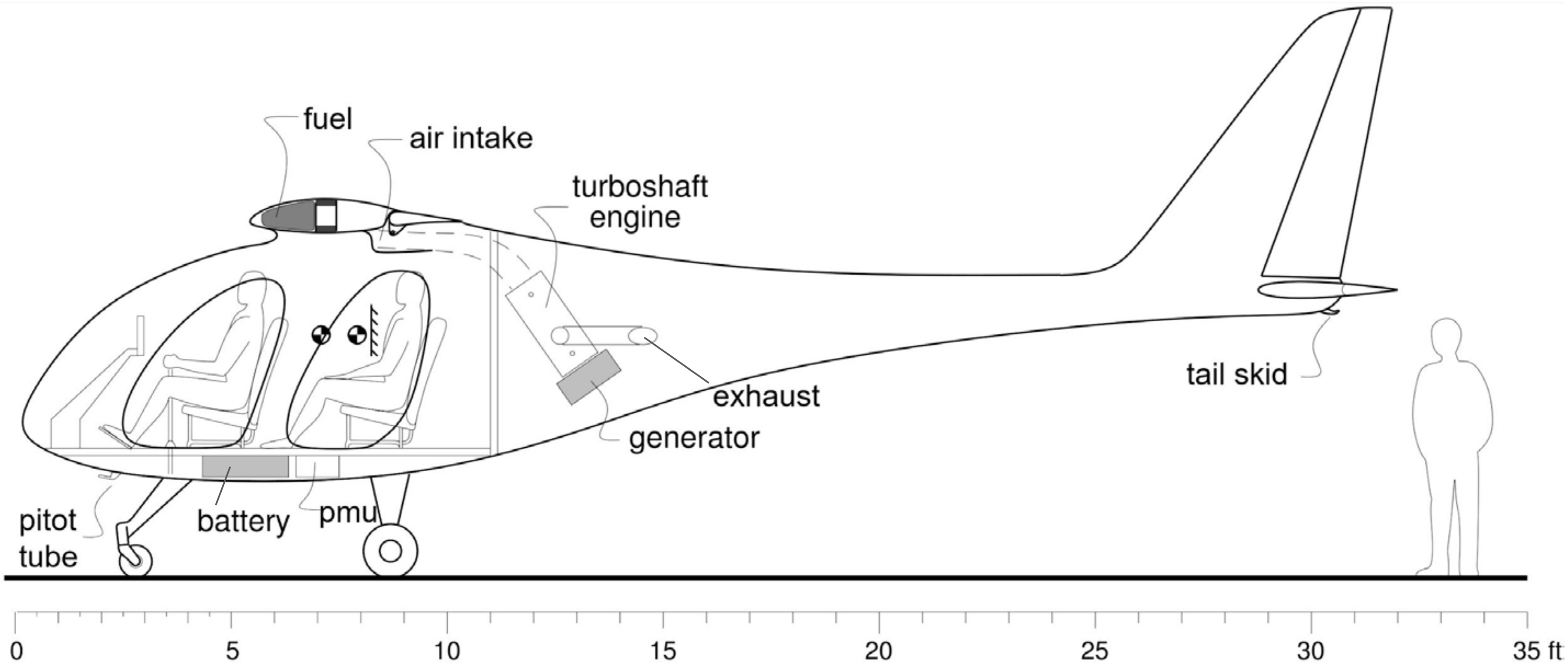
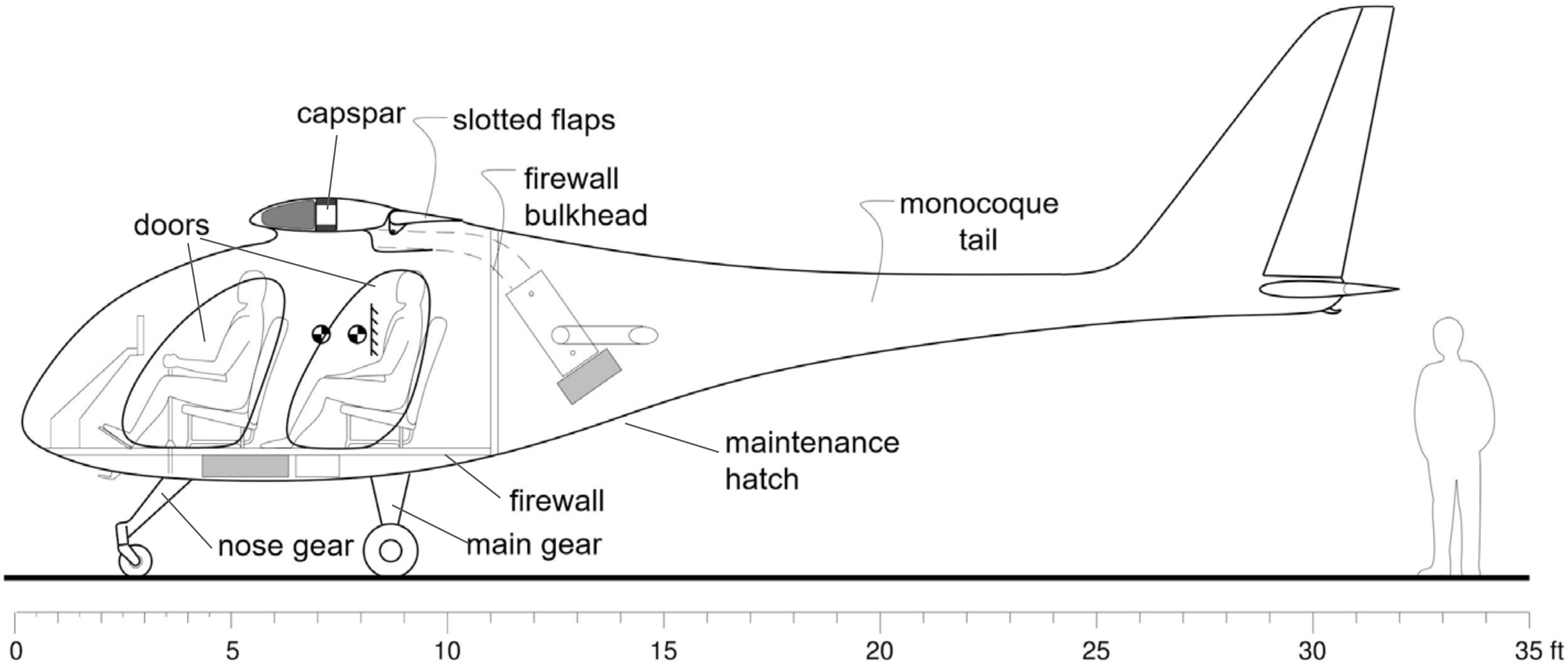
Aircraft Configuration

Components

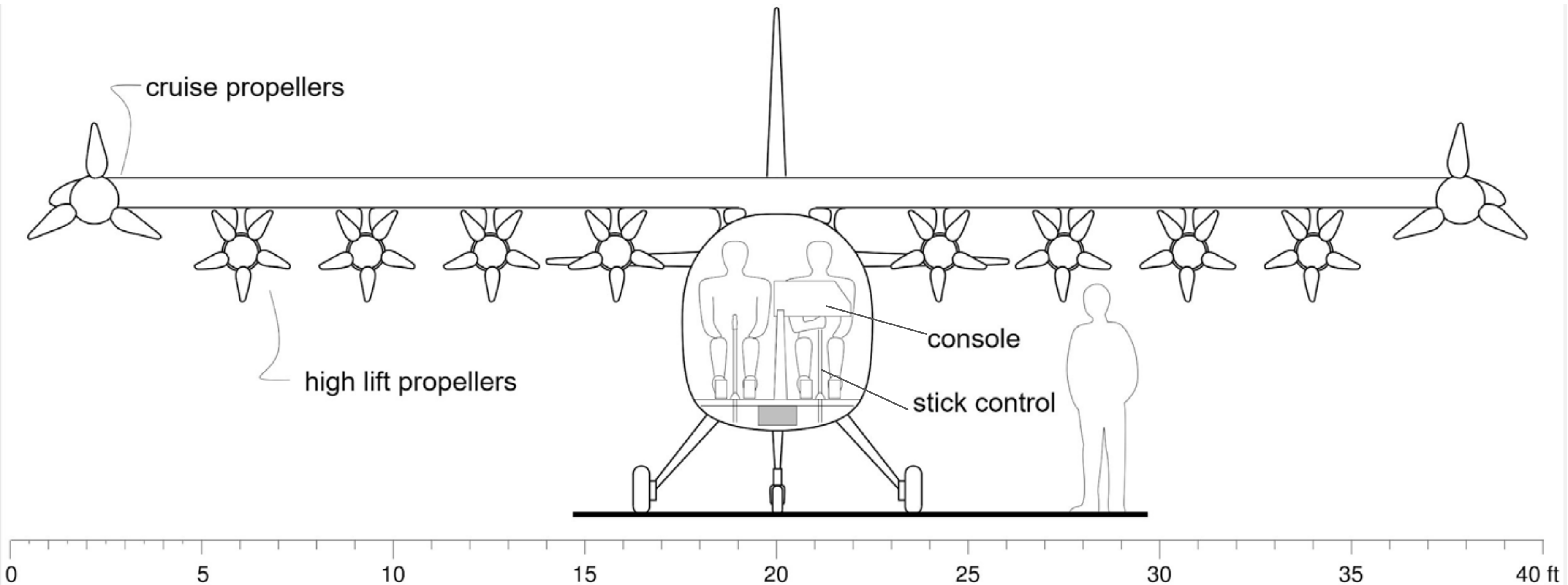


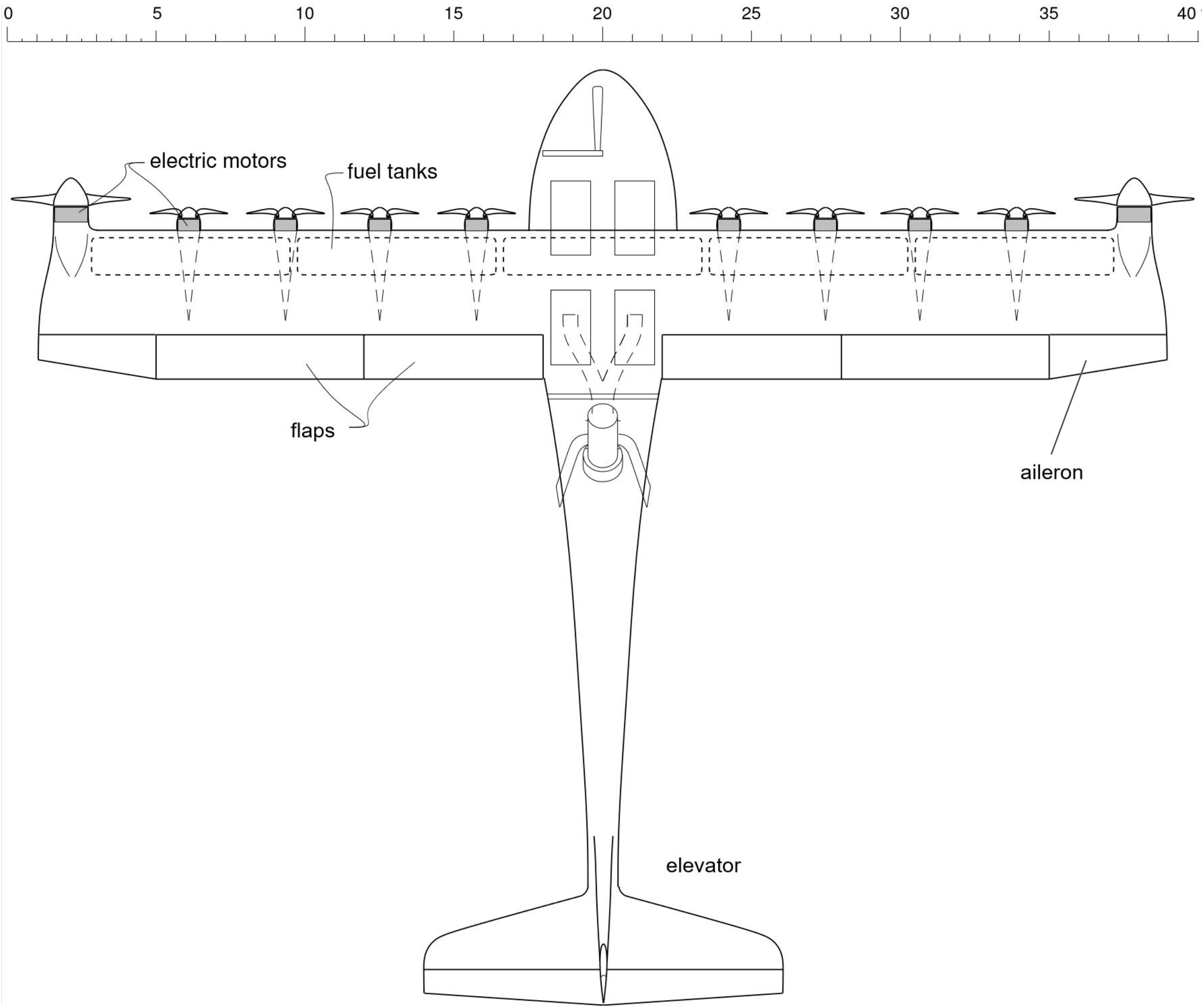
fuel
air intake
turboshaft engine
exhaust
generator
tail skid
pitot tube
battery
pmu
0
5
10
15
20
25
30
35 ft

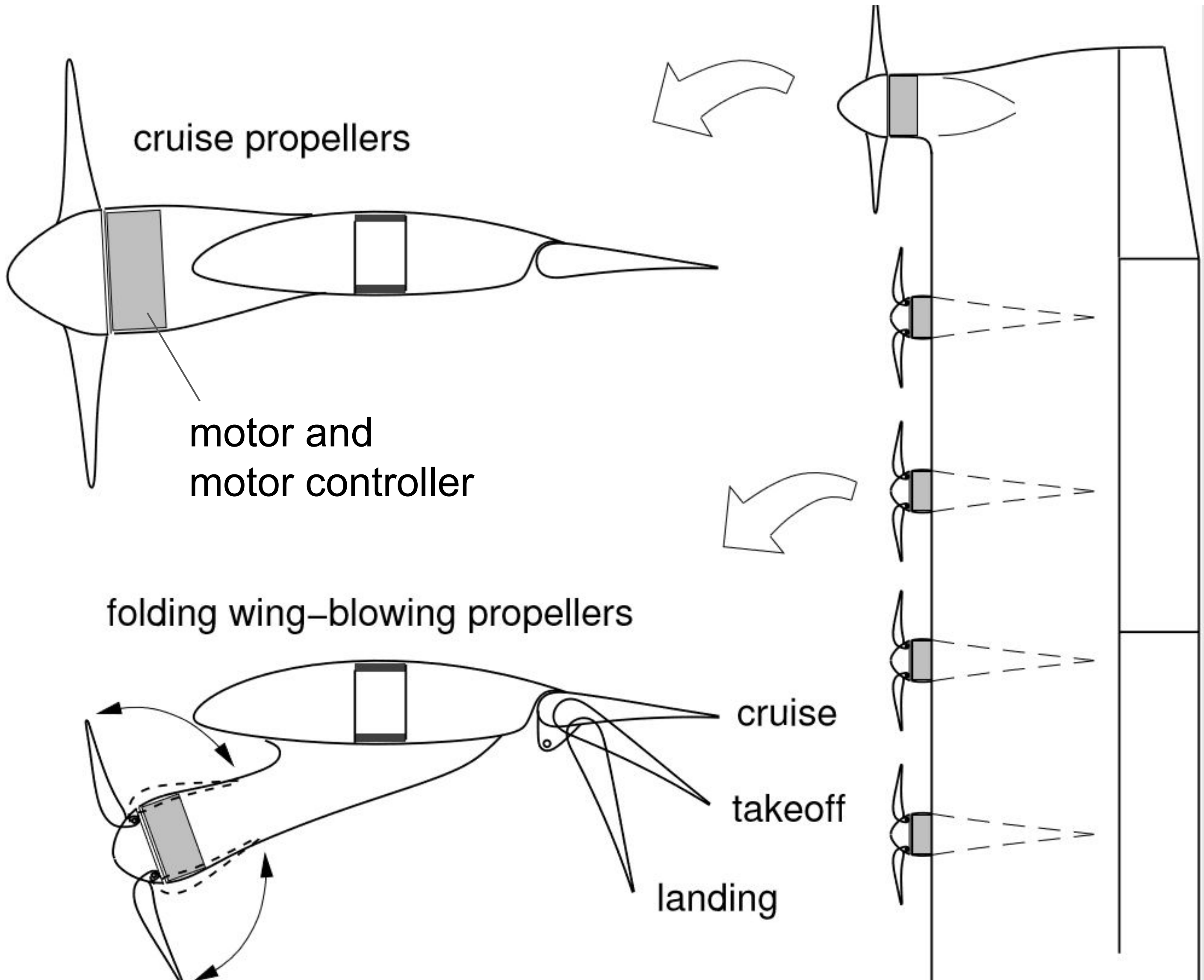
Structures


capspar
slotted flaps
firewall
bulkhead
monocoque
tail
doors
maintenance
hatch
firewall
nose gear
main gear
0
5
10
15
20
25
30
35 ft

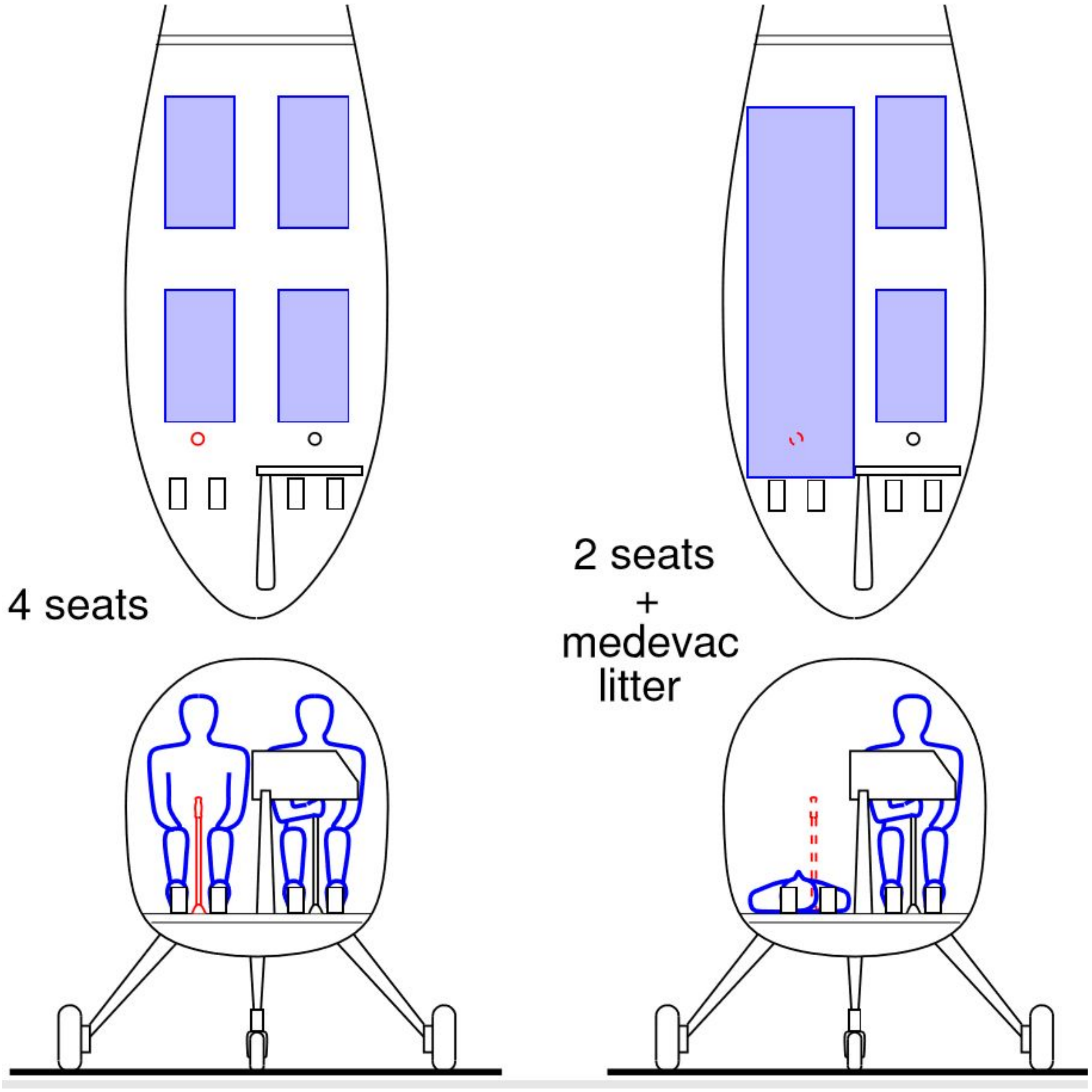
Propulsion


cruise propellers
high lift propellers
console
stick control
0
5
10
15
20
25
30
35
40 ft


0
5
10
15
20
25
30
35
40 ft
electric motors
fuel tanks
flaps
aileron
elevator



cruise propellers
motor and
motor controller
folding wing–blowing propellers
cruise
takeoff
landing


4 seats
2 seats
+
medevac
litter

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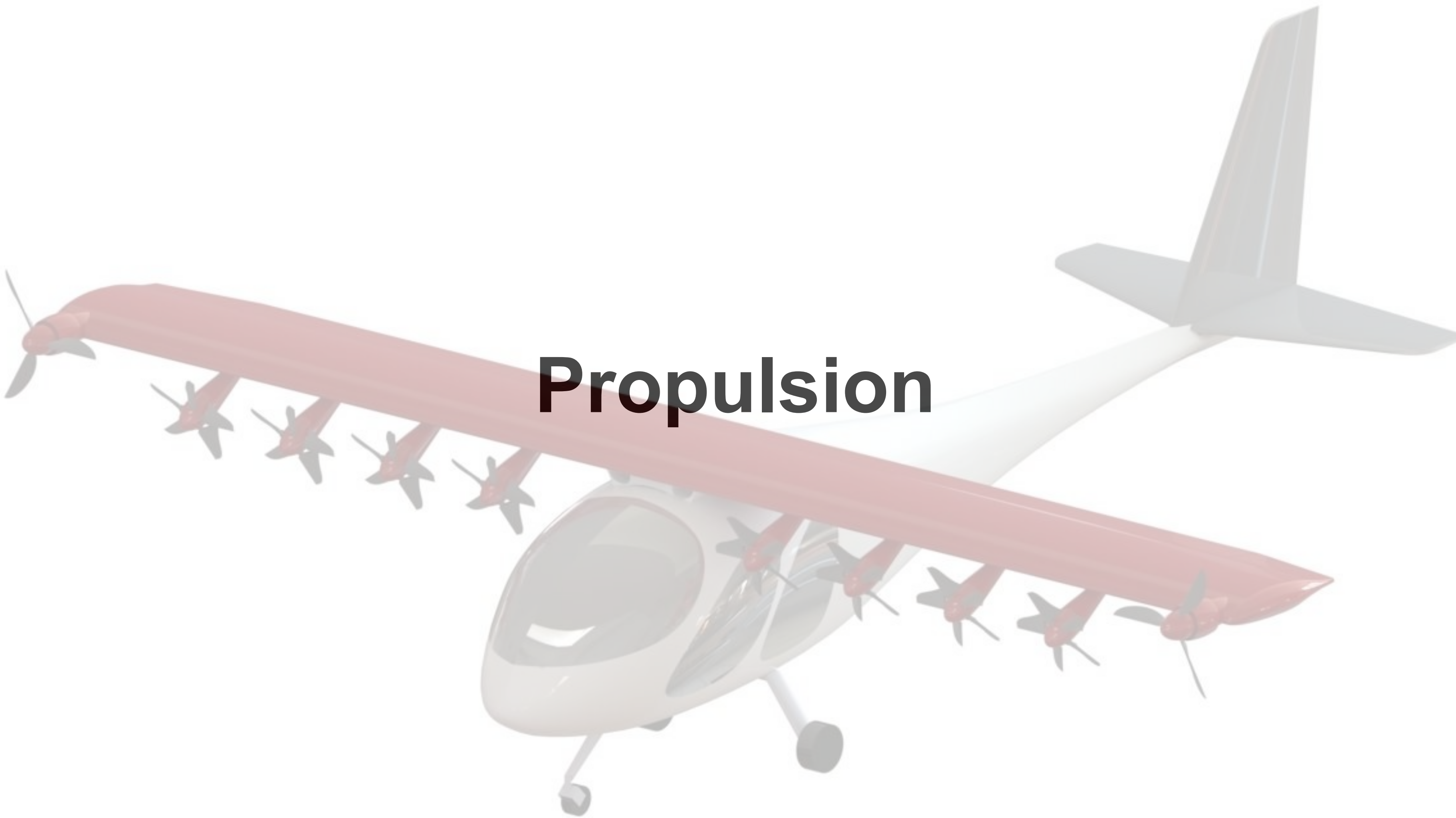
Propulsion

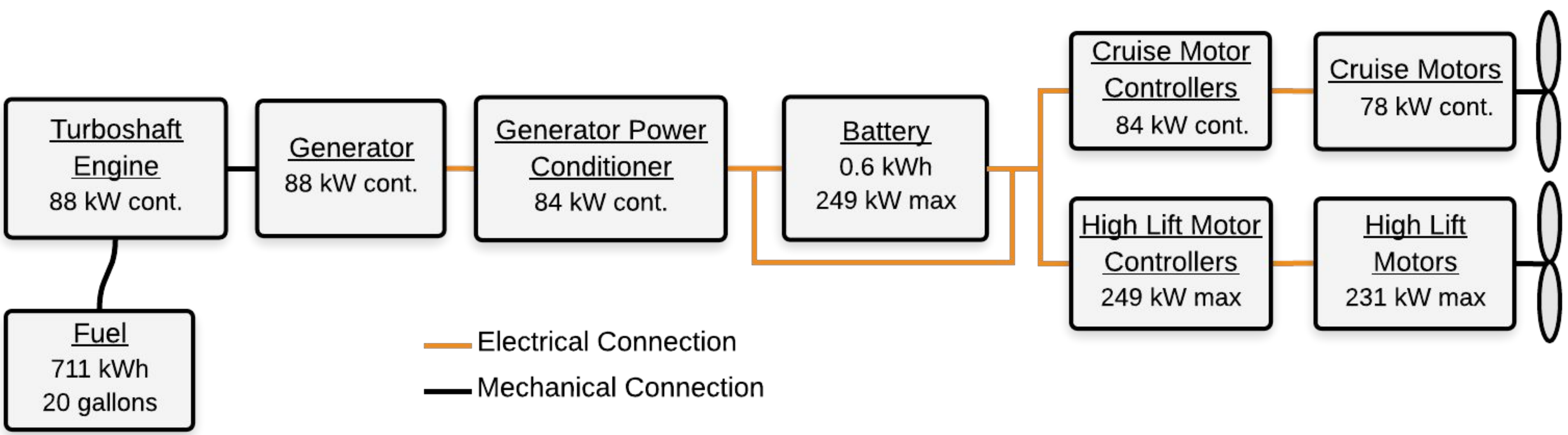


Propulsion Power Budget

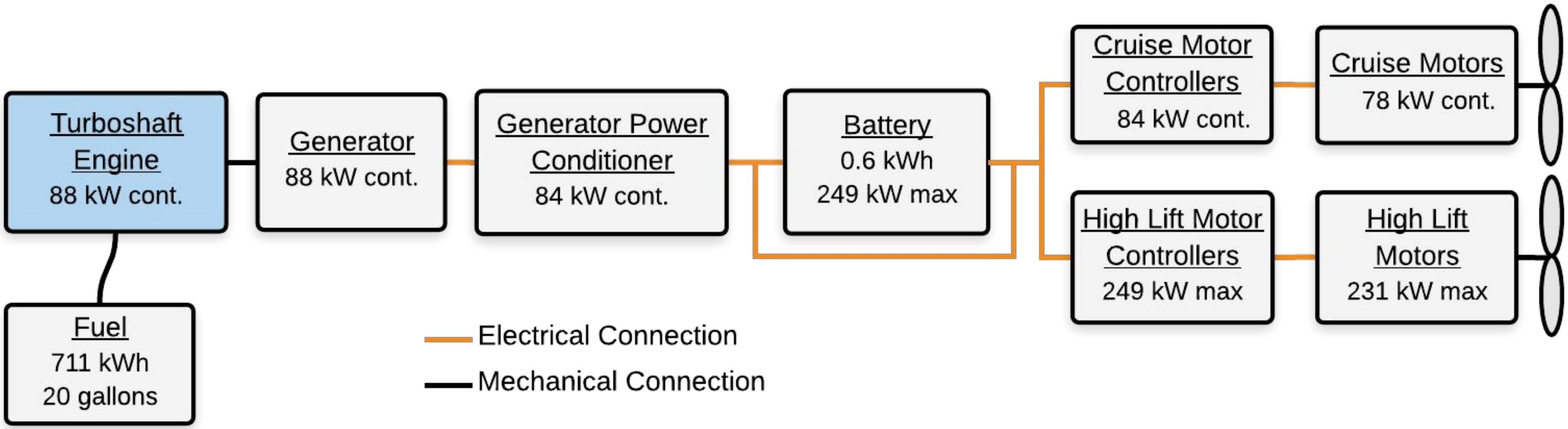
Mission Segment	Time of Segment	Battery Power [kW]	Engine Power [kW]	Total Output Power [kW]
Takeoff	3.4	230	84	309
Obstacle	1.9	230	84	309
Accelerate	27.1	89	84	156
Climb	165.4	0	84	76
Cruise	3000.0	0	84	76
Descent	174.2	0	84	76
Approach	56.7	0	84	76
Landing	5.0	230	84	309
Reserves	1800.0	0	63	56

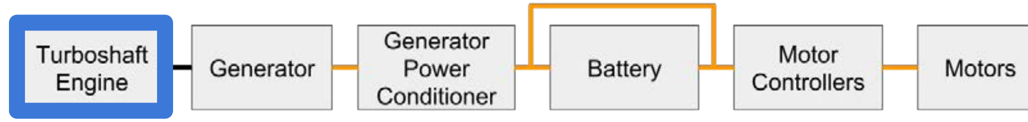
Powertrain Requirements

- System level requirements
  - Output power, cont. = 78 kW
  - Output power, max = 309 kW
  - Mission energy = 97 kWh
- Minimum component level requirements shown below



Component Selection





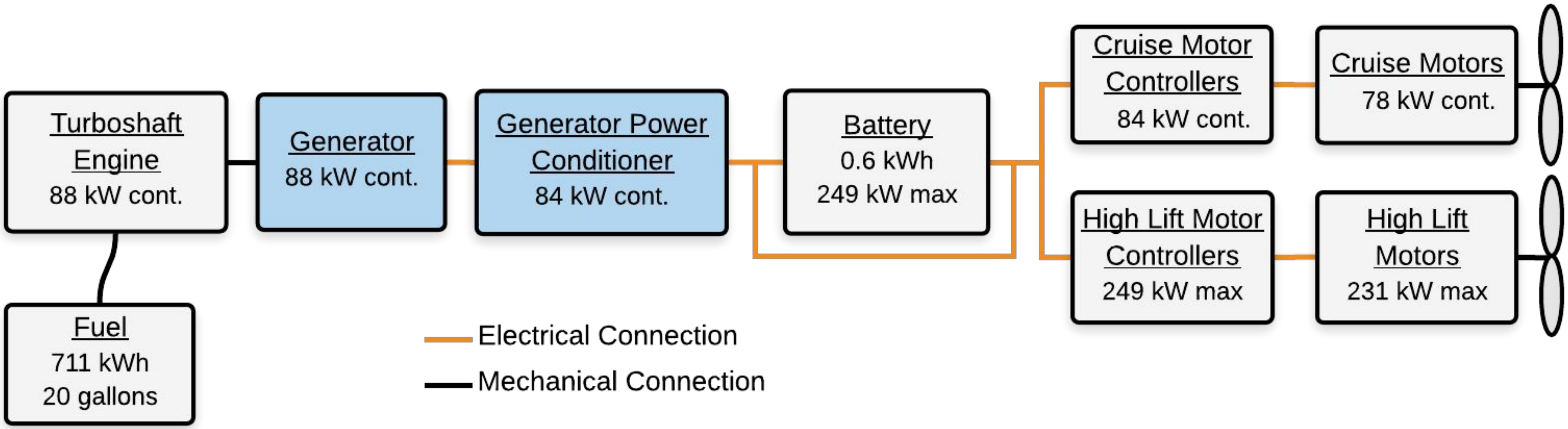
Turboshaft Engine

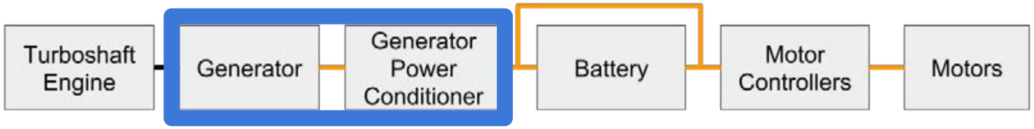
- Driving requirement - cont. power of **88 kW**
- Few options in this power class
- Allows for higher cruise velocities

Manufacturer	PBS Velka Bites
Model	TS 100DA
Power, max	180 kW
Power, cont.	**160 kW**
Mass	62.6 kg
SFC	0.525 kg/kW/h
Size (H x W x L)	16” x 13” x 33”

http://www.pbsvb.com/getattachment/Zakaznicka-odvetvi/Letectvi/Aircraft-UAV-engines/Turbohridelovy-motor-TS-100/PBS_Turboshaft-engine_TS100_EN.pdf.aspx

Component Selection



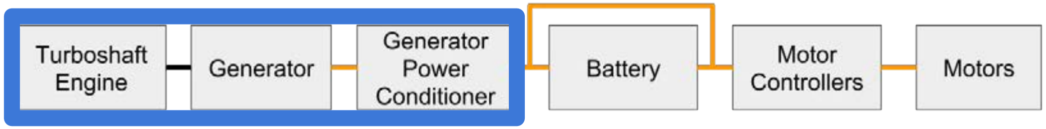


Integrated Generator and Power Conditioner

- Updated requirement - cont. power of **160 kW**
- Selected component specs

Manufacturer	MAGicALL
Model	MAGiDRIVE 300
Power, max (120s)	300 kW
Power, cont.	**240 kW**
Mass	49.5 kg
Typical Efficiency	95.3%
Cooling	Air cooled through fins
Size	18.4” diameter 7.6” length

http://www.magicall.biz/downloads/magidrive-datasheet.pdf

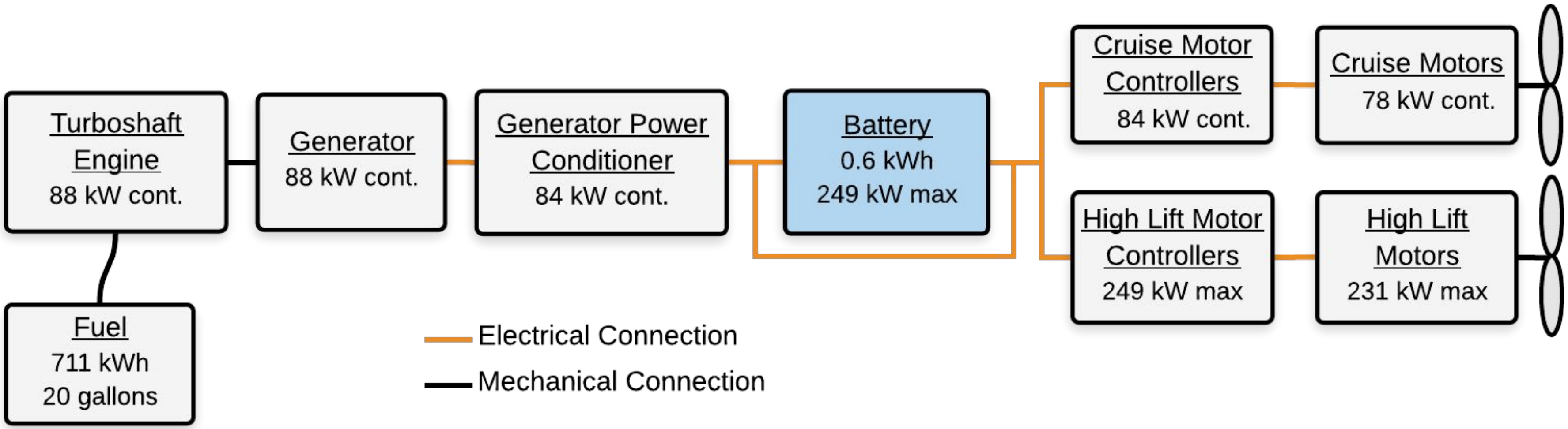


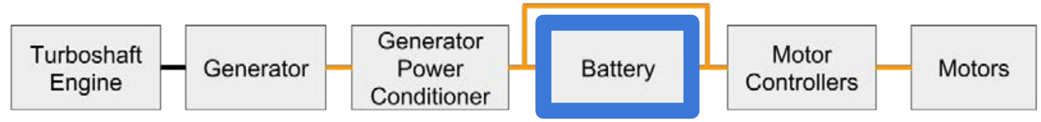
Turboshaft - Generator RPM and Torque Matching

- Turboshaft engine has built-in gearbox
- Components placed directly in line
  - Reduce shaft transmission losses

	Turboshaft	Generator
RPM, max	2158	3600
Torque, max [Nm]	797	1000

Component Selection



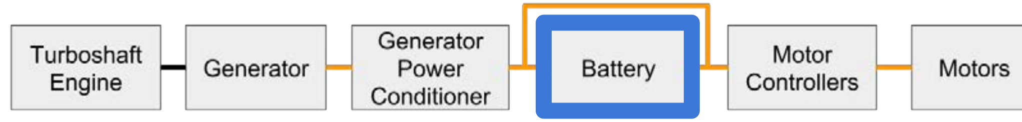


Battery - Cell Level

- Driving requirement - highest specific power available
- Selected cell specs

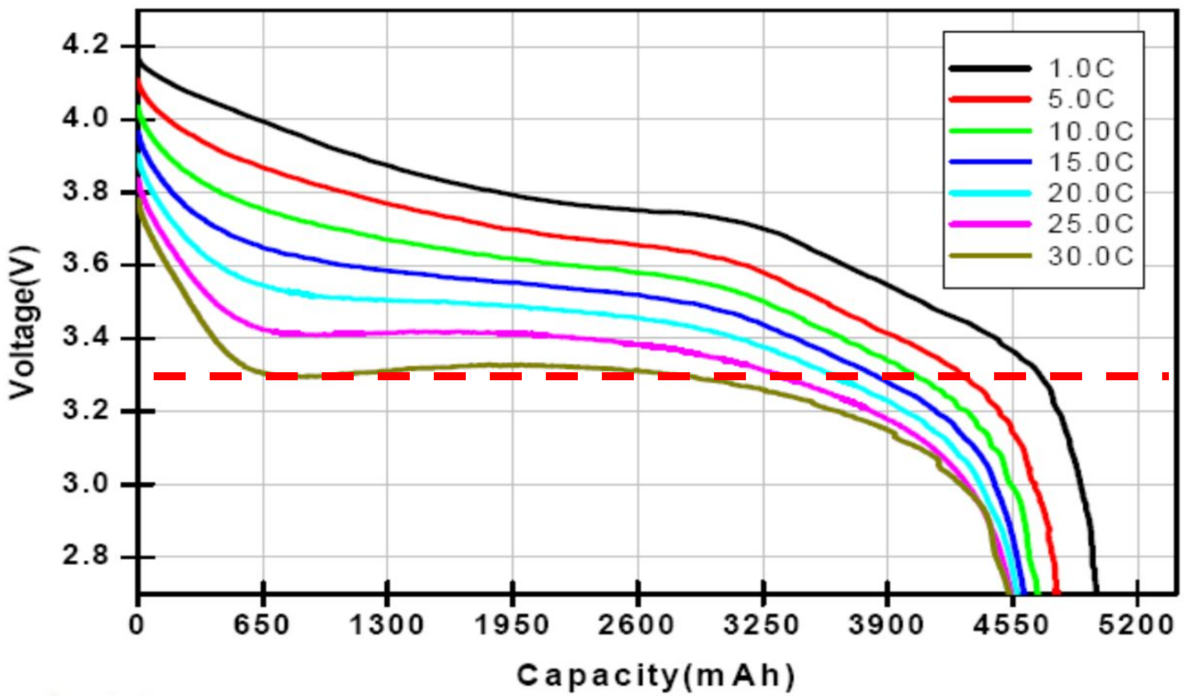
Manufacturer	Kokam
Model	SLPB11543140H5
Chemistry	Lithium nickel manganese cobalt oxide (NMC)
Nominal Voltage	3.7 V
Capacity	5 Ah
Internal Resistance	3 mΩ
C-Rate, cont.	30
Specific Power, cont.	**3.9 kW/kg**
Mass	128 g

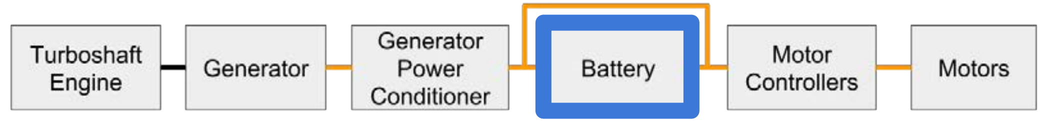
http://kokam.com/data/Kokam_Cell_Brochure_V.4.pdf



Battery - Cell Level Discharge Curves

- Operate at 30C rate
  - Average cell voltage of 3.3V
  - Specific power of **3.9 kW/kg**
  - Specific energy of **117 Wh/kg**

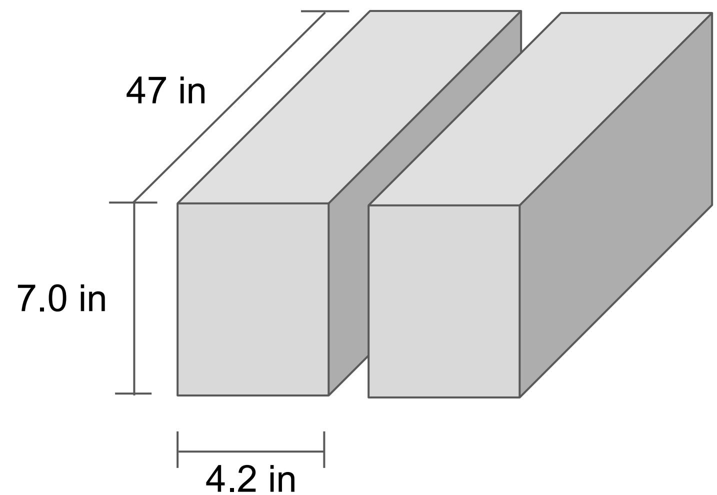


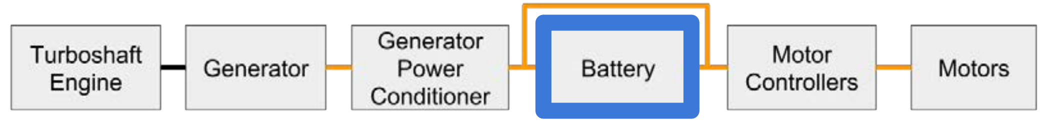


Battery - System Level

- Updated requirement - max power of **161 kW** total
- Two parallel strings, physically separated into two packs

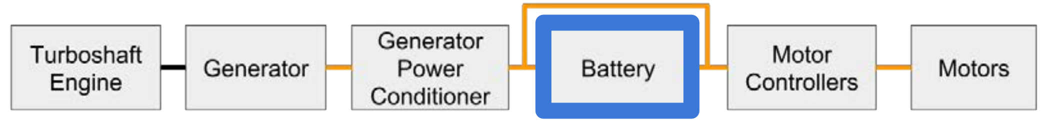
Cell Configuration	164S2P
Power, max	**162 kW**
Cell Mass	42 kg
Pack Mass	53 kg
Voltage, OCV	688 V
Voltage, During discharge	541 V
Capacity	10 Ah
Cooling	Not required





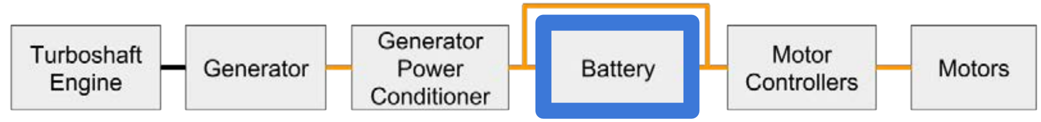
Battery - Discharging Operations

- Takeoff and obstacle
  - 30C discharge for 5.3 sec
  - 0.22 Ah used
- Landing
  - 30C discharge for 5 sec
  - 0.21 Ah used
- Total
  - 0.43 Ah used
  - **Depth-of-Discharge (DOD) = 8.6%**
  - **12.4 min recharge time**



Battery - Charging Operations

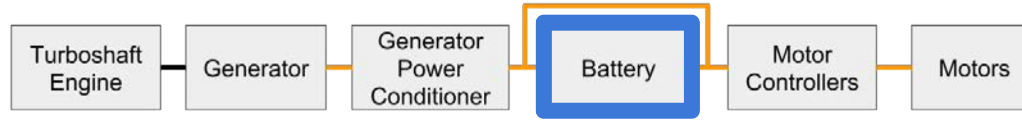
- Low DOD ➡ stays within constant voltage (CV) portion of charging regime
    - Requires average 12.6 kW of turboshaft power
- Charge during climb and cruise
    - 72 kW excess turboshaft power available



Battery - Charging Operations

- Proposed battery mission profile

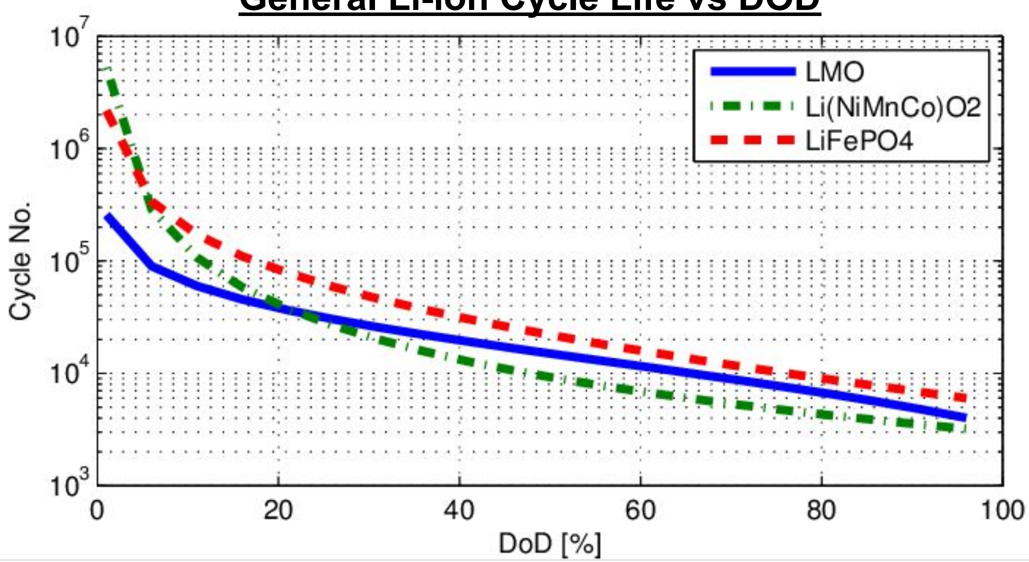
Flight Phase	Time	Charge / Discharge Rate	Battery SOC (at end of phase)
Landing	5.0 s	-30C	95.8%
Turnaround	~5 min		95.8%
Takeoff & Obstacle	5.3 s	-20C	91.4%
Climb	2.8 min	CV at 4.2V	98%
Cruise	9.6 min	CV at 4.2V	100%



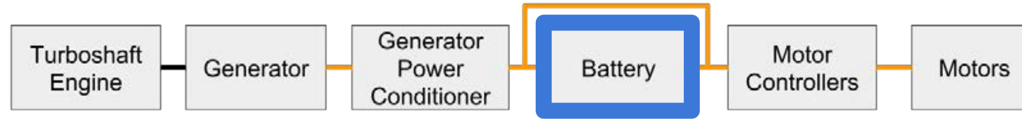
Battery - Cycle Life

- Cell rated for 1000 cycles at 95% DOD
- Cell actually cycles at 5% DOD
    - Expect 100,000 to 1,000,000 cycles
    - Note: full battery capacity not needed
- **Battery will last entire life of airplane**

General Li-ion Cycle Life vs DOD



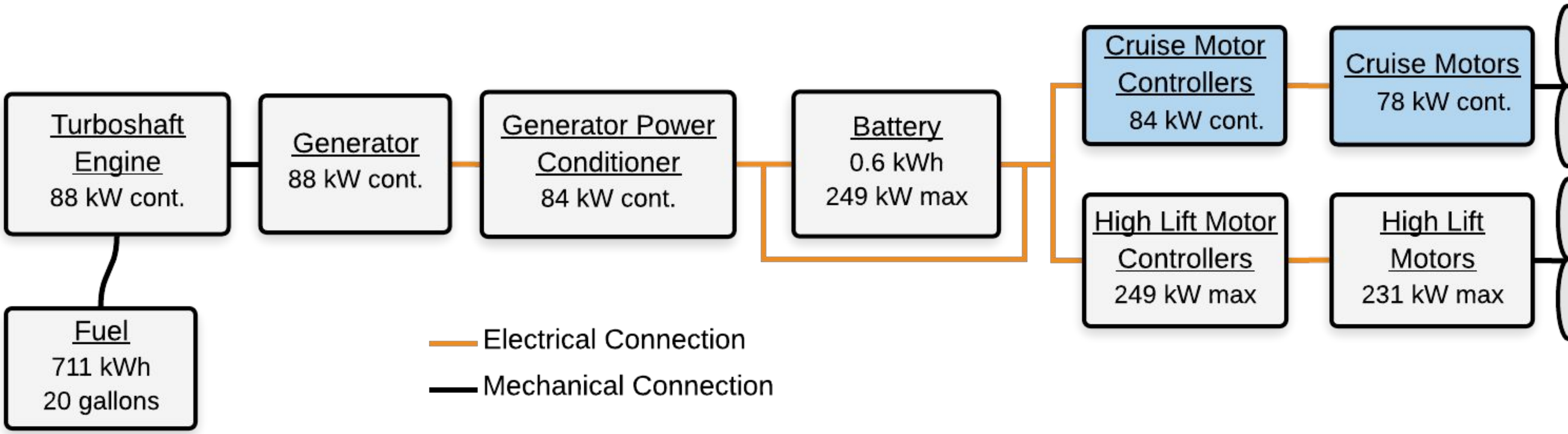
https://www.researchgate.net/publication/303890624_Modeling_of_Lithium-Ion_Battery_Degradation_for_Cell_Life_Assessment

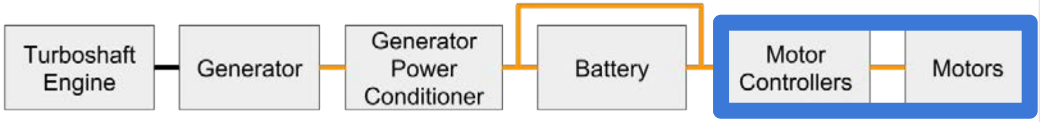


Ni-MH Battery Option

	Li-ion (design cell)	Ni-MH (certification option)
Power	161 kW	161 kW
Energy	4.9 kWh	11.6 kWh
Depth of Discharge	8.6 %	3.8 %
Charging Time	12.4 min	2 min
Cycle Life	100,000 to 1,000,000	5,000 to 10,000
Mass	53 kg	301 kg

Component Selection

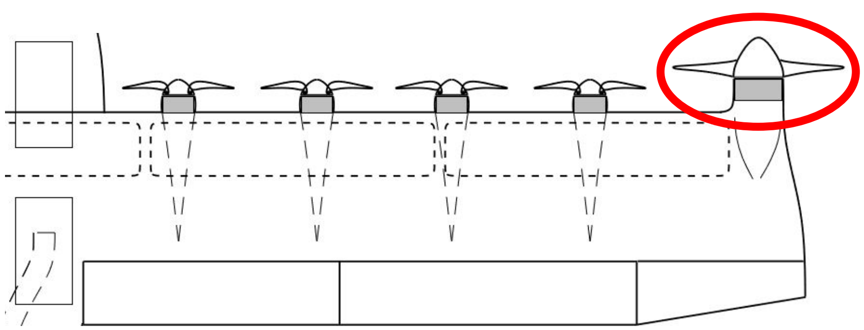


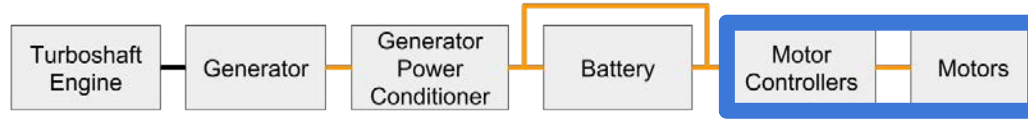


Cruise - Propeller

- 2 fixed-pitch propellers, 3 blades each
- 1.2 m (47.2”) diameter

- Designed for cruise (120 kt, 499 N)
  - 2507 RPM (M_{tip} = 0.5), 133 Nm
  - η = 89% → 36% at takeoff



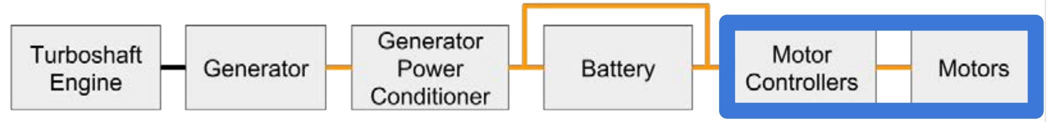


Cruise - Integrated Motor and Controller

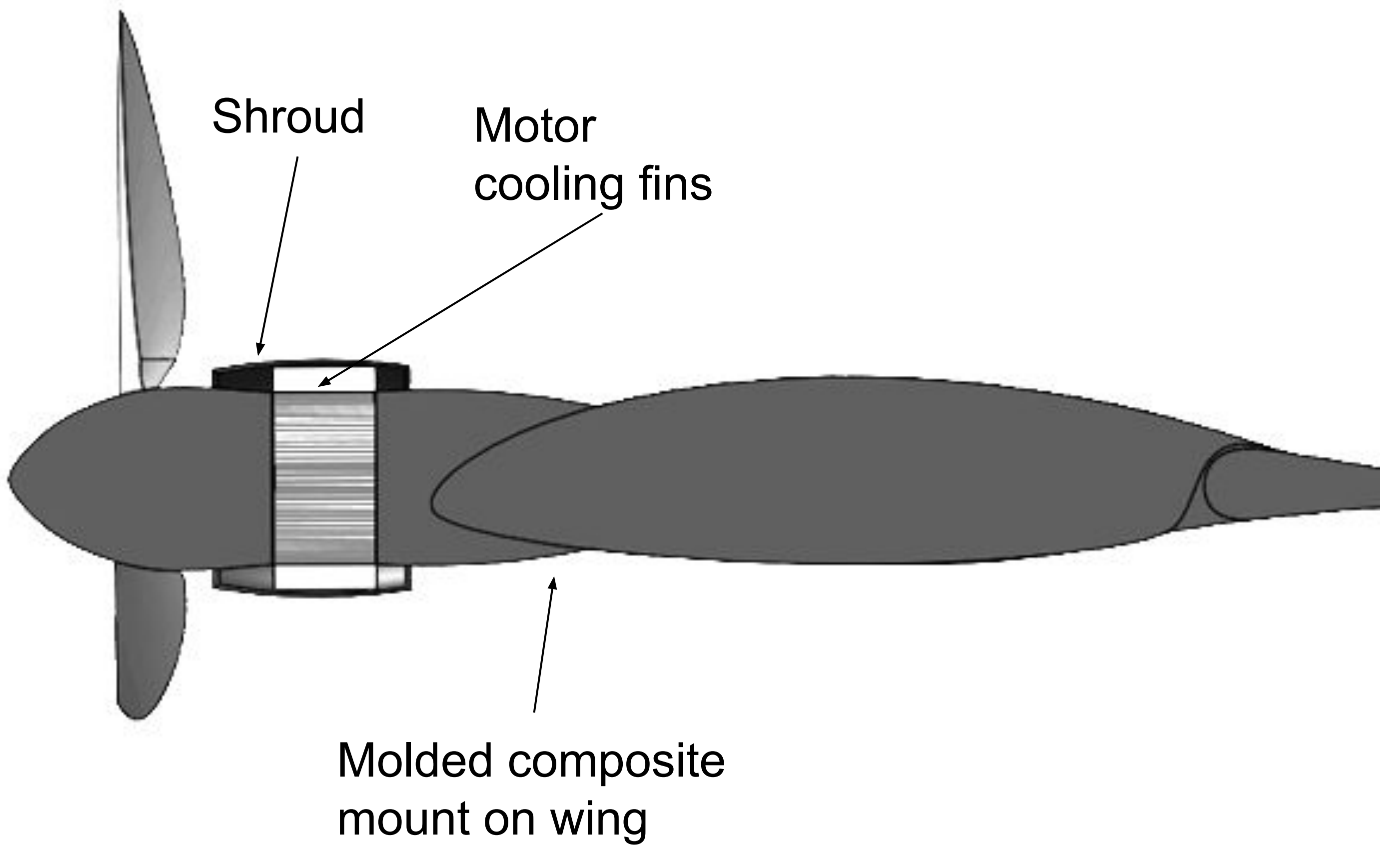
- Driving requirement - 133 Nm of torque at 2507 RPM

Manufacturer	MAGicALL
Model	MAGiDRIVE 75
Torque	146 Nm
RPM, max	5,000
Mass	12.1 kg
Typical Efficiency	93.5%
Cooling	Air cooled through fins
Size	11” diameter 5.2” length

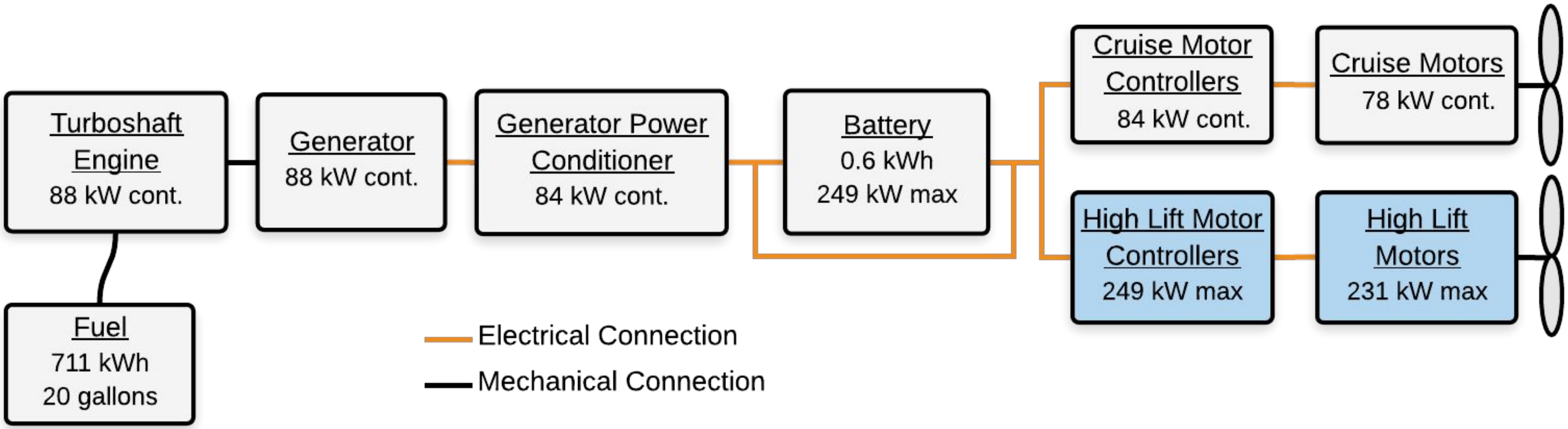
http://www.magicall.biz/downloads/magidrive-datasheet.pdf

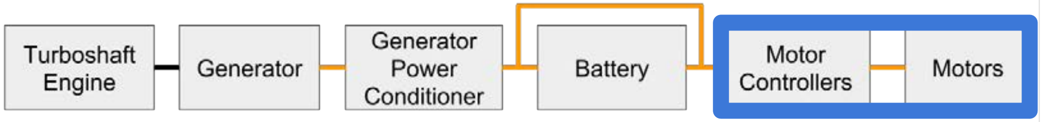


Cruise - Motor Mounting and Cooling



Component Selection

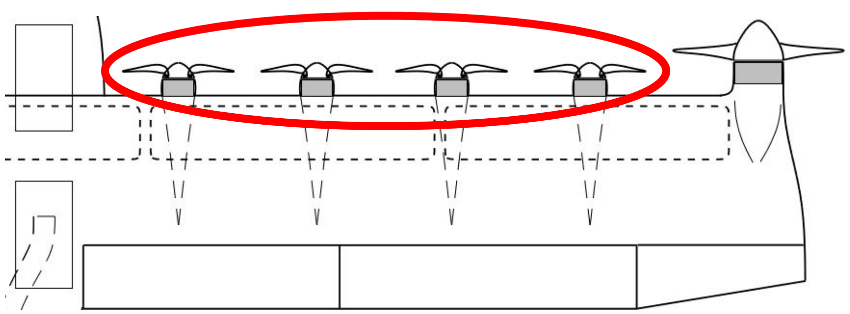




High Lift - Propeller

- 8 fixed-pitch propellers, 5 blades each
- Fold backward during cruise
- 0.8 m (31.5”) diameter

- Designed for takeoff (28 kt, 597 N)
  - 4059 RPM (M_{tip} = 0.5), 51 Nm

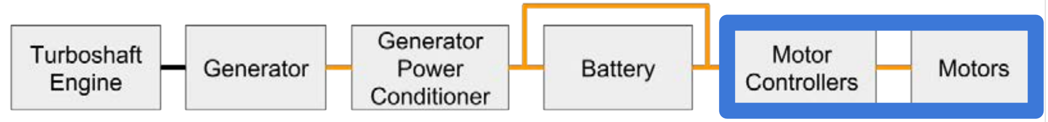


High Lift - Integrated Motor and Controller

- Driving requirement - 51 Nm of torque at 4059 RPM

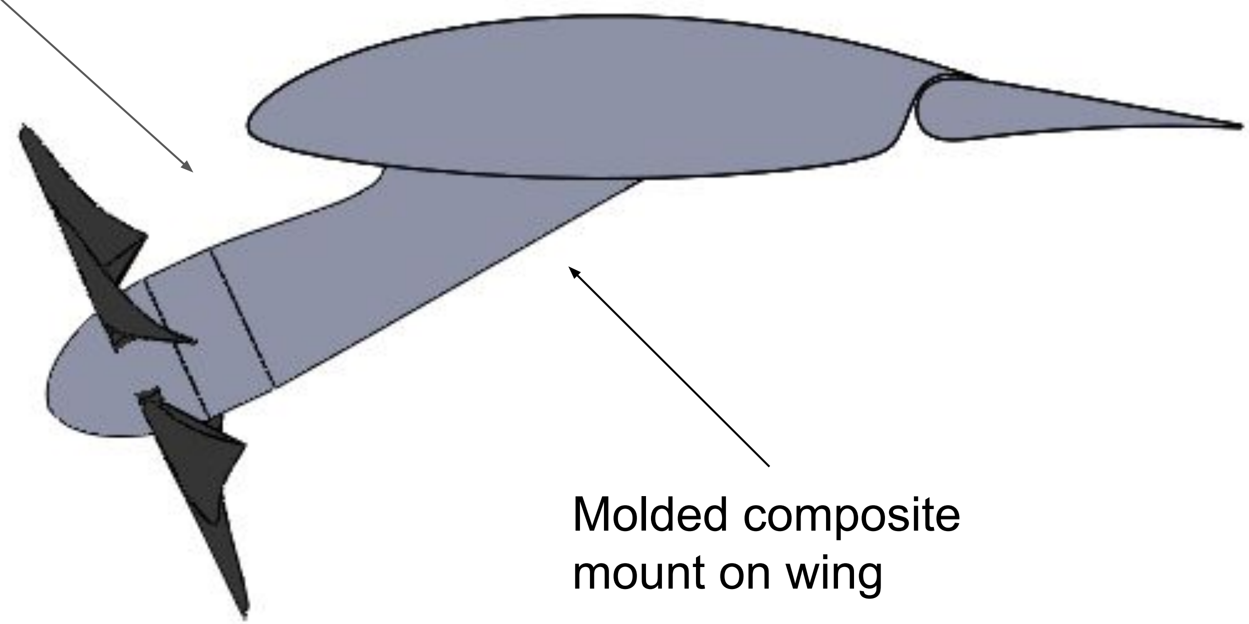
Manufacturer	MAGicALL
Model	MAGiDRIVE 40
Torque	56 Nm
RPM, max	5,500
Mass	5.8 kg
Typical Efficiency	92.5%
Cooling	Air cooled through fins
Size	8.8” diameter 4.2” length

http://www.magicall.biz/downloads/magidrive-datasheet.pdf



High Lift - Motor Mounting

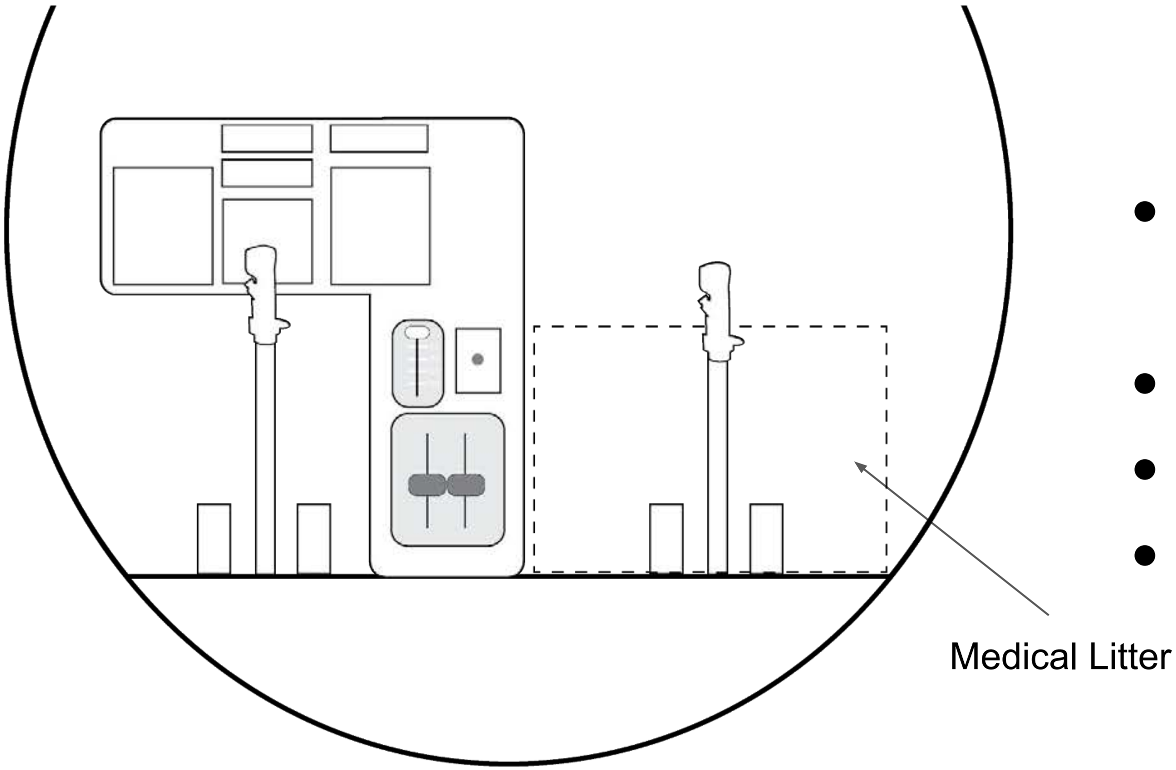
Angled parallel to streamlines during blowing



Molded composite mount on wing

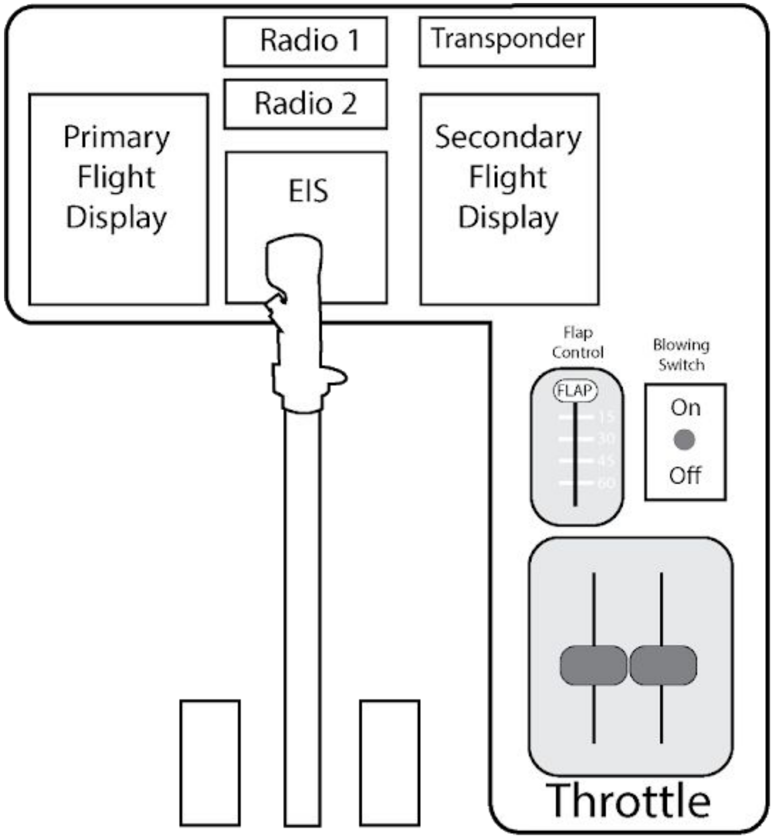
Aircraft Controls

Cockpit Controls & Design



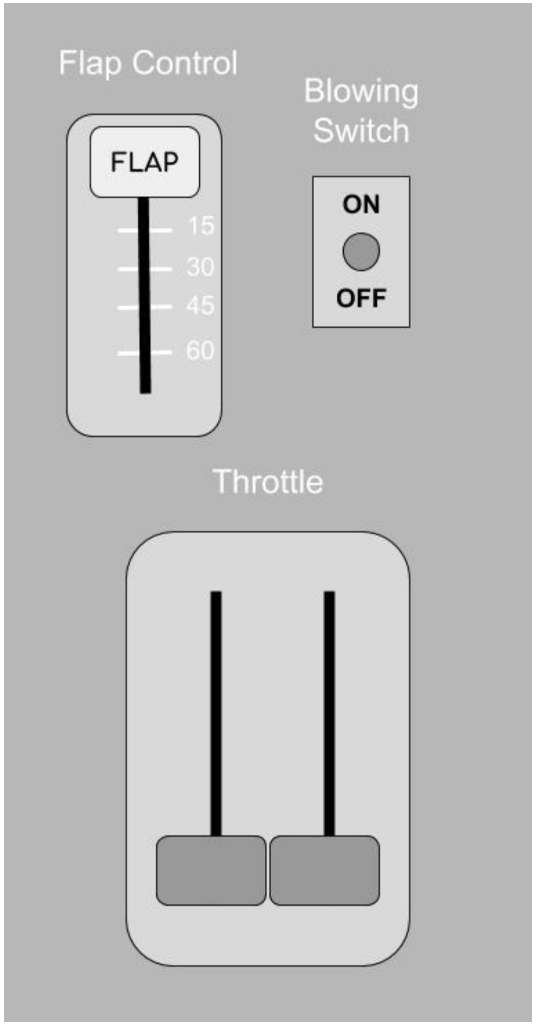
- Space for medical litter next to pilot
- Mechanical cable system
- Stick control
- Rudder pedals

Cockpit Controls & Design

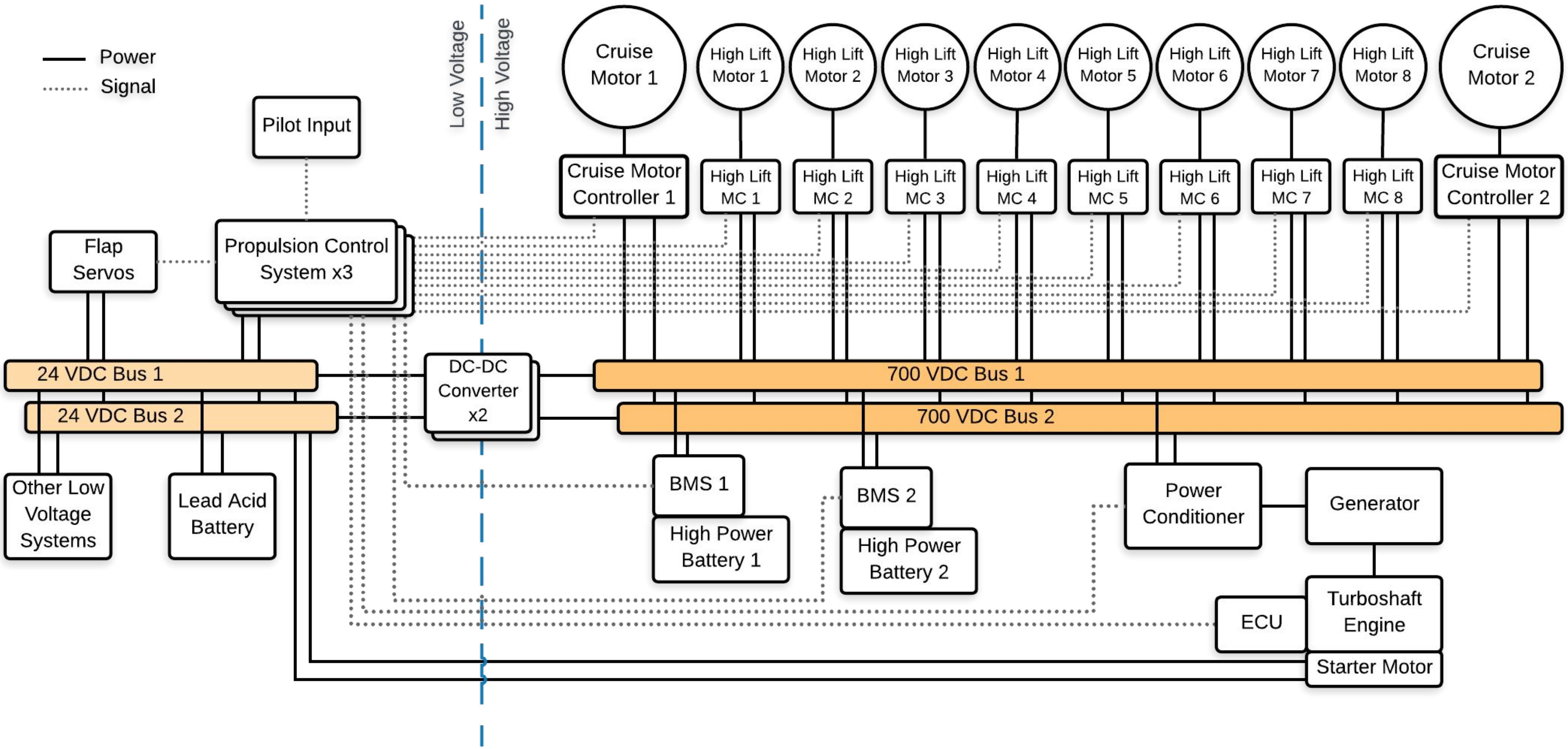


Propulsion Control System

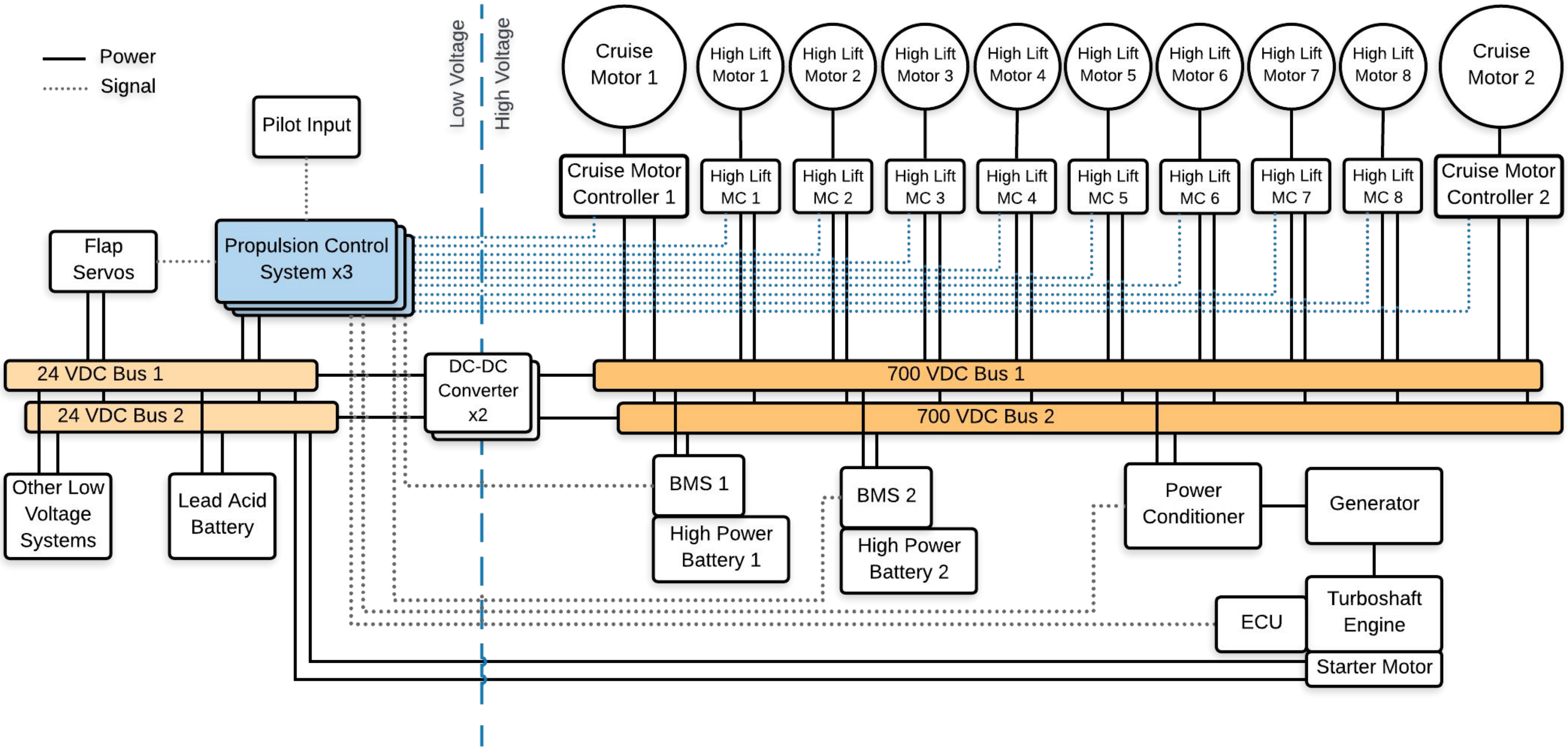
- Propulsion throttle controls outer motors
- Manual flap deployment
    - High Lift/Drag lever
    - Blowing scheduled to flap deflection
    - Weight on wheels cuts off blowing
- Switch gives option to manually turn off blowing



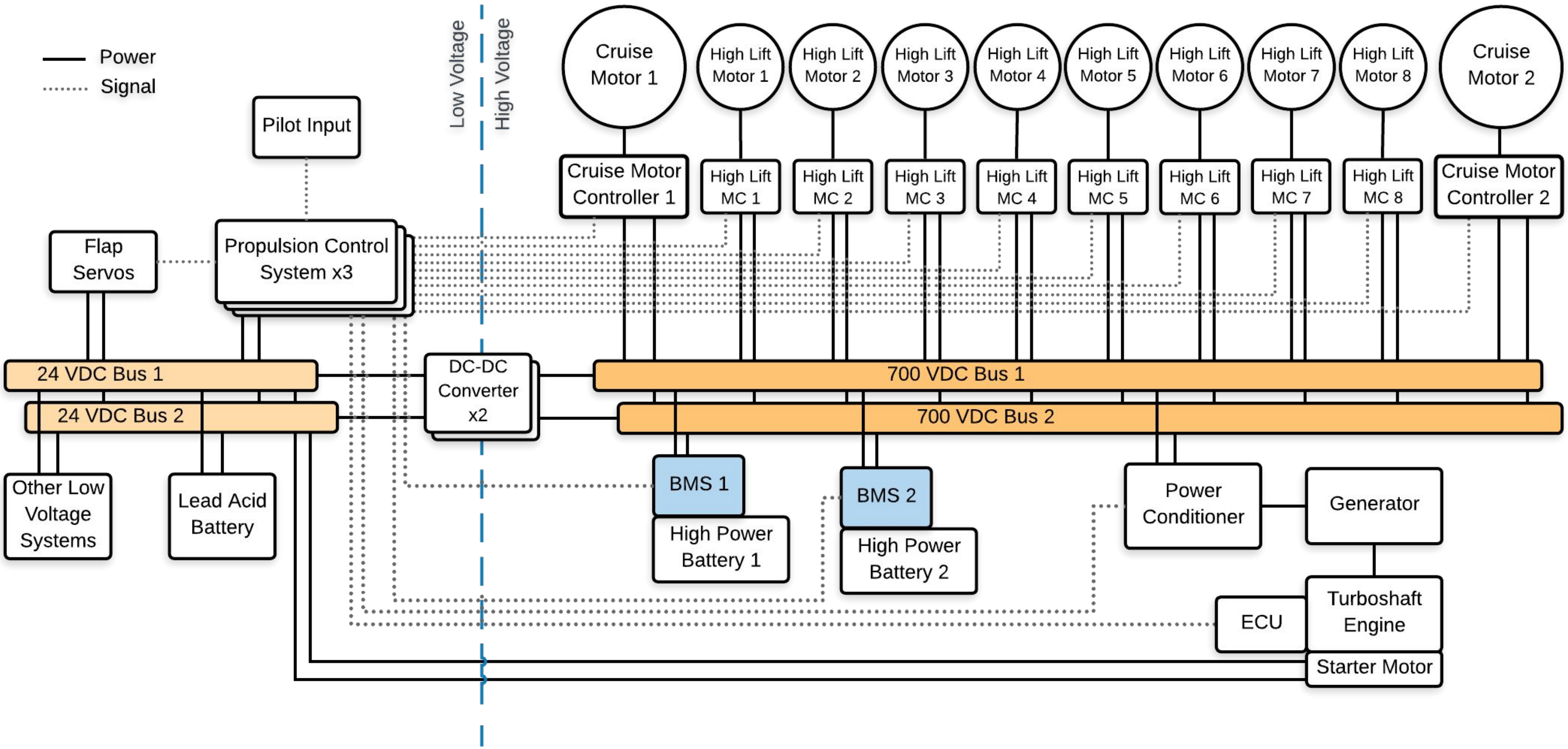
Propulsion Control System



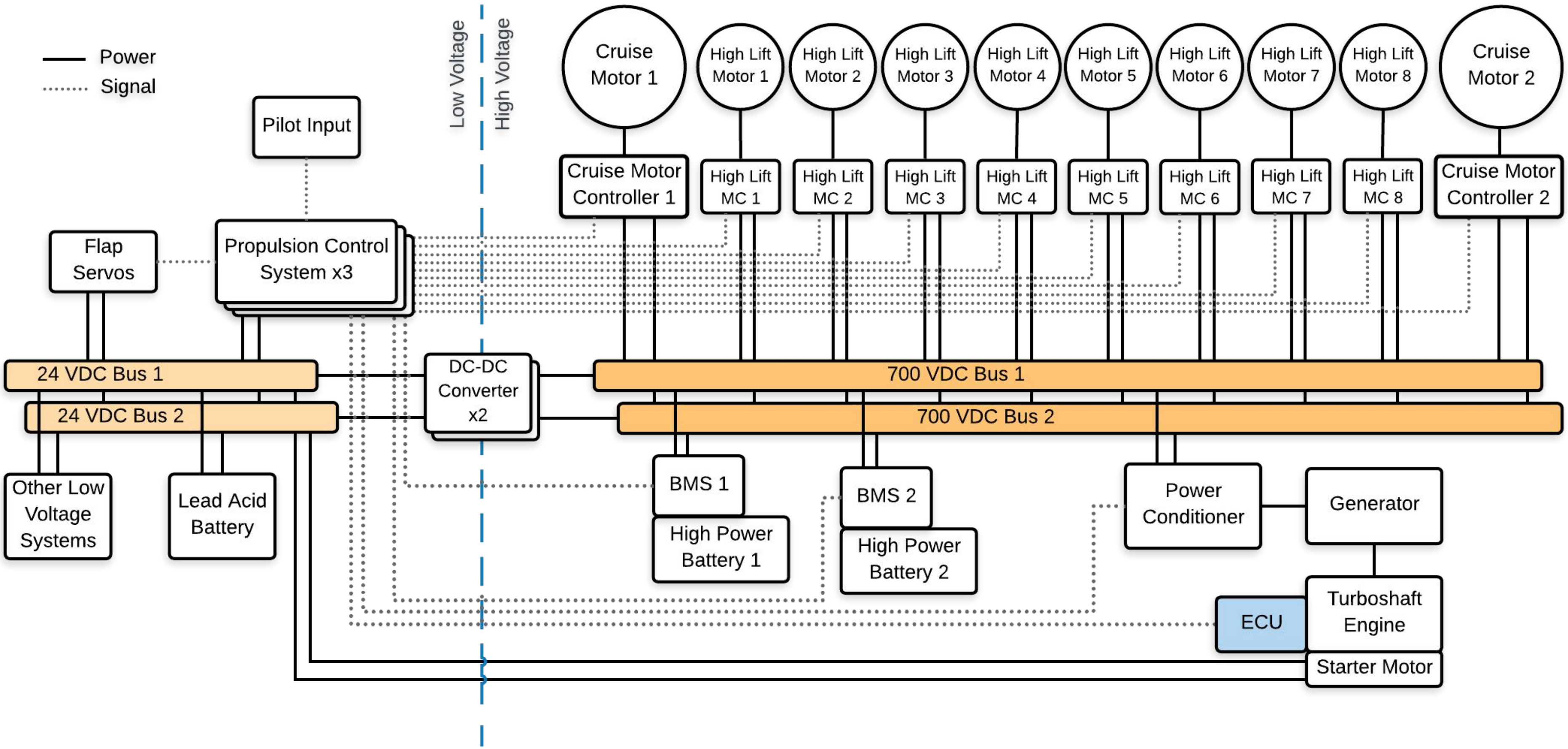
Propulsion Control System - Motors



Propulsion Control System - BMS



Propulsion Control System - ECU

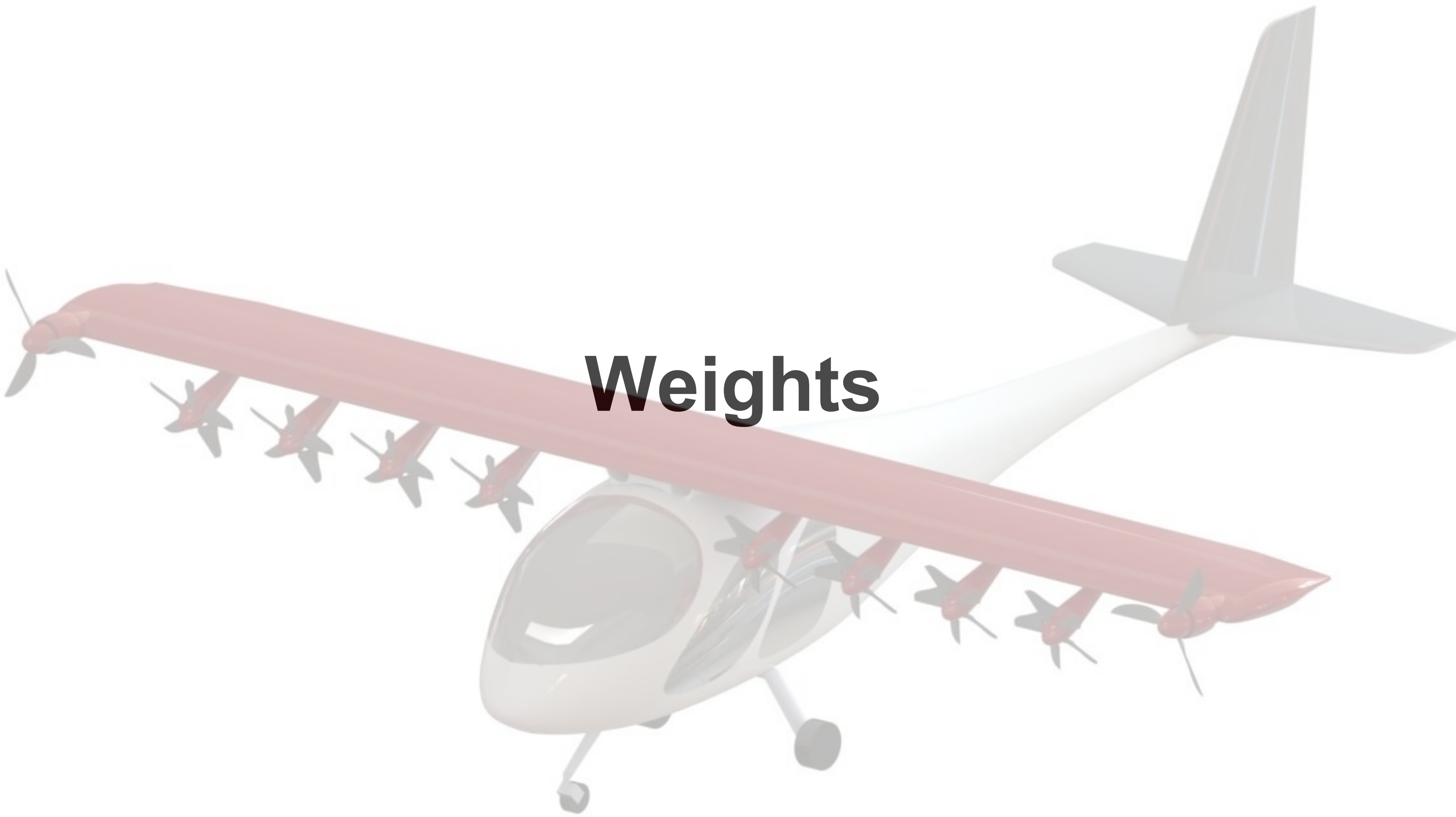


Propulsion System Failure Modes - Motors

- Cruise motor/controller failure during cruise
  - Automatically transfer power to outermost high lift motors
- High lift motor failure during takeoff/landing
  - Automatically increase power to remaining high lift motors

Propulsion System Failure Modes - Power Sources

- Single battery pack failure
  - Can operate at 76% of normal maximum power
- Dual battery pack failure
  - Can operate at 52% of normal maximum power
- Turboshaft or generator failure
  - Transition to battery power
  - ~5 min of flight at reserve speed available



Weights

Structural Group Weight

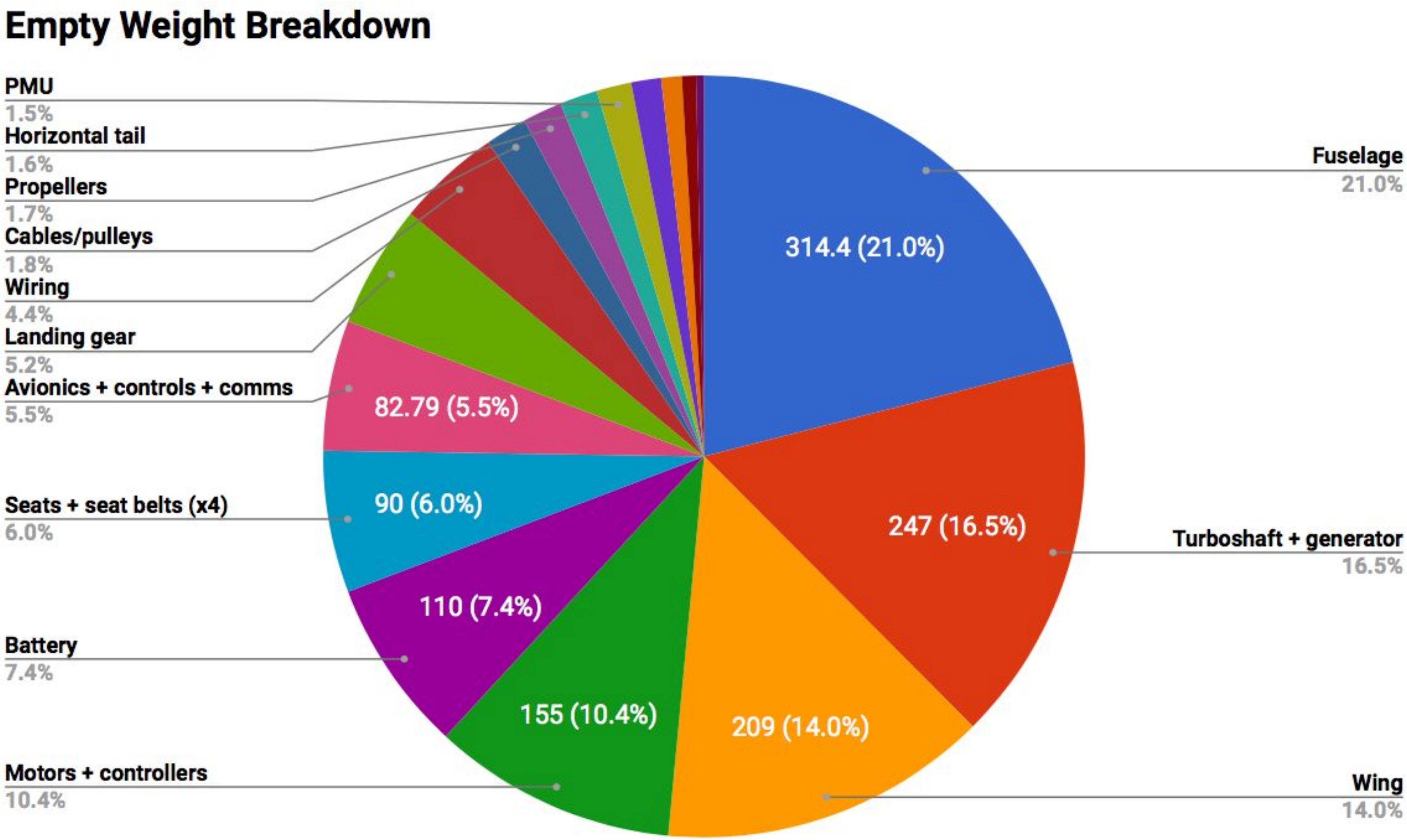
Part	Weight [kg]	Weight [lb]	Source
Fuselage	141	314	SR22 structure/surface area estimates with margin
Wing	94	209	GPkit structural model
Landing gear	35	78	C172 gear w/brakes and fairings
Horizontal tail	11	24	GPkit structural model
Tailboom	9	20	GPkit structural model
Vertical tail	4	9	GPkit structural model
Total	**294**	**654**	

Propulsion Group Weight

Part	Weight [kg]	Weight [lb]	Source
Turboshaft + generator	111	247	Part sourcing
Motors + controllers	71	155	Part sourcing
Battery	50	110	Power sizing
Wiring	30	66	Estimated wire size and length
Propellers	11	25	Prop/folding mechanism weight
PMU	10	22	Reasonable estimate
Fuel tanks	6	13	Based on fuel volume (20 gal)
Total	**287**	**638**	

Equipment Group Weight

Part	Weight [kg]	Weight [lb]	Source
Seats + seatbelts	40	90	Part sourcing (DA40)
Avionics + controls + comms	37	83	Part sourcing + 7% margin
Cables + pulleys	12	27	Standard aircraft cables/pulleys, estimated length + 25% margin
Oil	2	5	2.5 quarts of oil
Total	**92**	**204**	


Empty Weight Breakdown
PMU
1.5%
Horizontal tail
1.6%
Propellers
1.7%
Cables/pulleys
1.8%
Wiring
4.4%
Landing gear
5.2%
Avionics + controls + comms
5.5%
Seats + seat belts (x4)
6.0%
Battery
7.4%
Motors + controllers
10.4%
Fuselage
21.0%
Turboshaft + generator
16.5%
Wing
14.0%
314.4 (21.0%)
247 (16.5%)
209 (14.0%)
155 (10.4%)
110 (7.4%)
90 (6.0%)
82.79 (5.5%)

Useful Load Weight

Item	Weight [kg]	Weight [lb]	Source
Passengers (3)	276	614	FAA, 92 kg/person
Pilot	92	204	FAA, 92 kg/person
Fuel	59	132	GPkit fuel estimate, ~20 gal
Baggage	36	80	FAA, 9 kg/person
Total	**463**	**1030**	

FAA AC 120-27E:
https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC120-27E.pdf

Weight Rollup

Group	Weight [kg]	Weight [lb]
Structure	295	655
Propulsion	287	638
Equipment	92	204
Empty weight	**674**	**1497**
Useful load	463	1030
Margin	75	167
MTOW	**1222**	**2694**

DA-40

	Weight [kg]	Weight [lb]
Empty weight	786	1746
Useful load	405	900
MTOW	1190	2646

SR22

	Weight [kg]	Weight [lb]
Empty weight	1013	2250
Useful load	517	1150
MTOW	1530	3400

https://www.diamondaircraft.com/wp-content/uploads/2016/11/Diamond-Brochure-DA40-XLT.pdf

Outline

1. Motivation
2. General Overview
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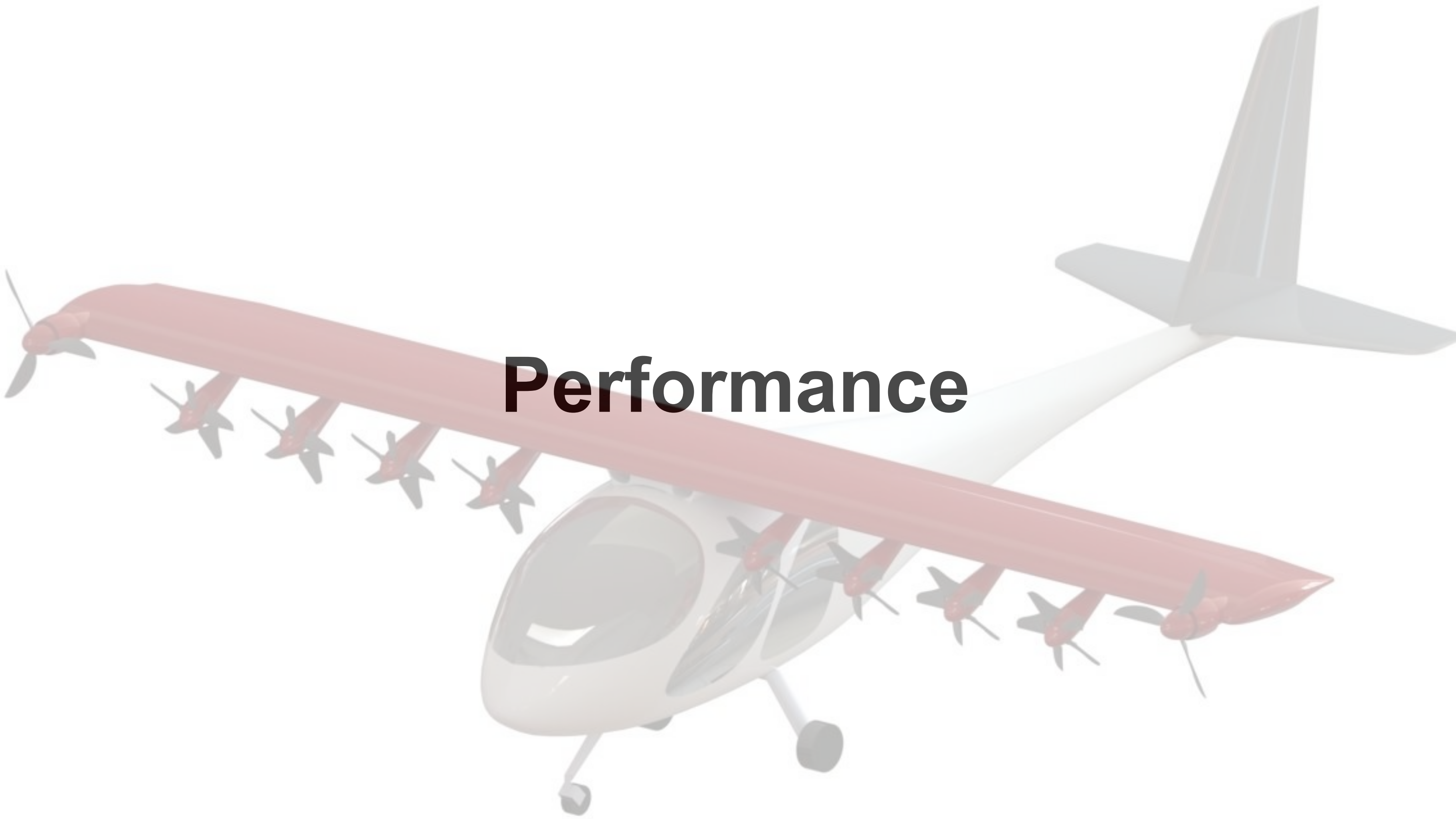
5. Subsystems
6. **Performance**
7. Risk
8. Conclusion

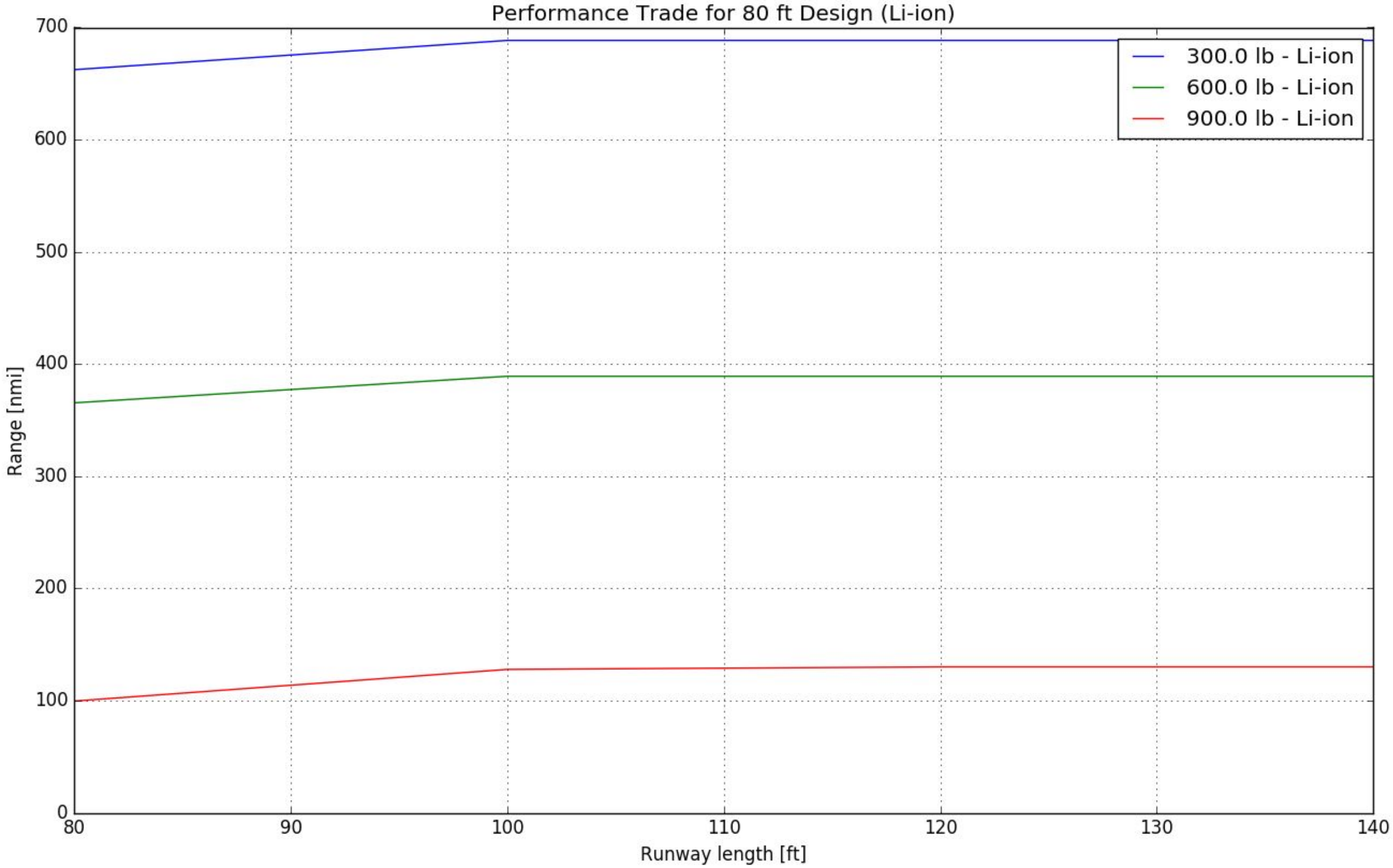
Performance



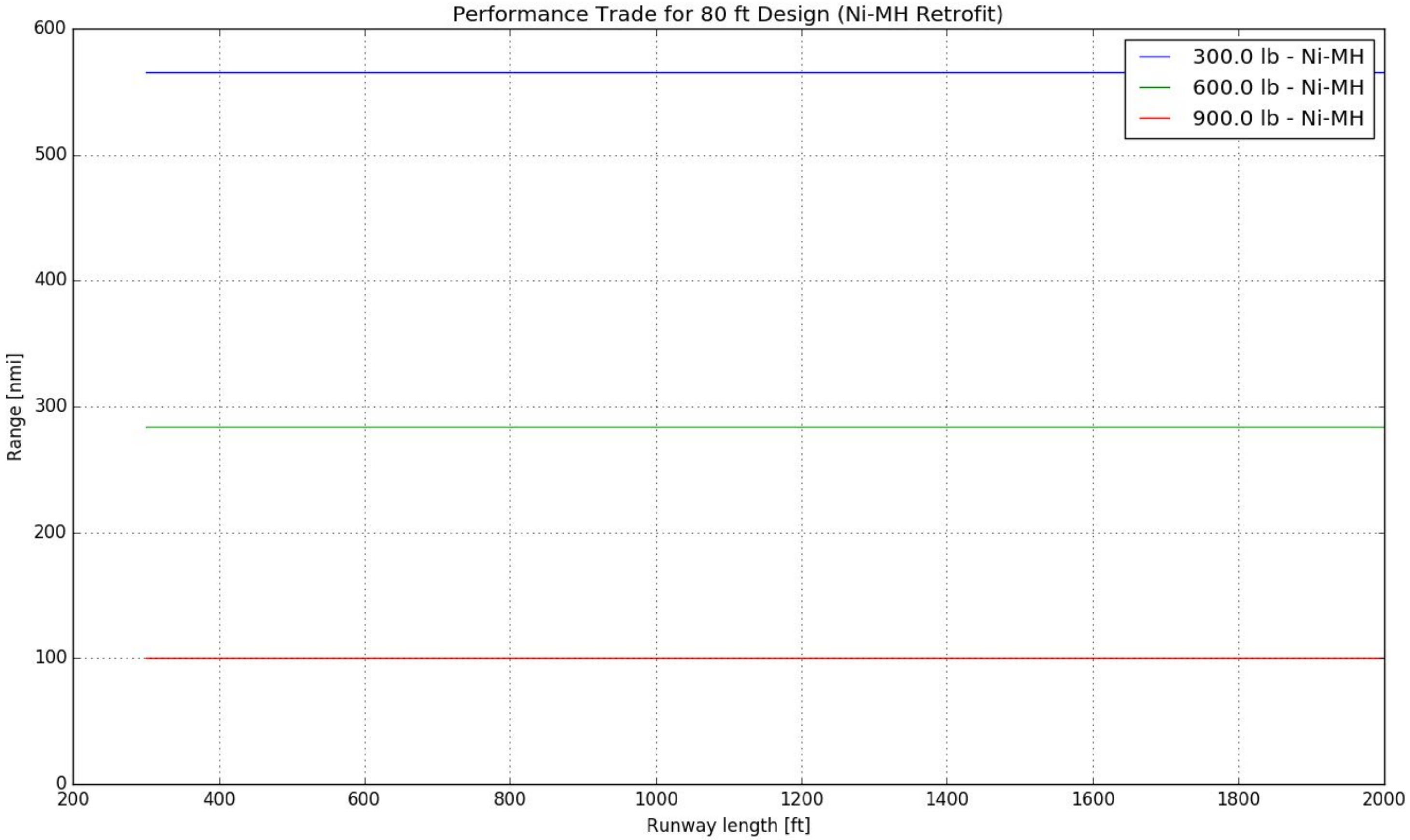
Li-ion vs Ni-MH

	Li-ion (design cell)	**Ni-MH (certification option)**
Mass	1222 kg	1450 kg
Runway	80 ft	134 ft
50 ft Obstacle	180 ft	234 ft

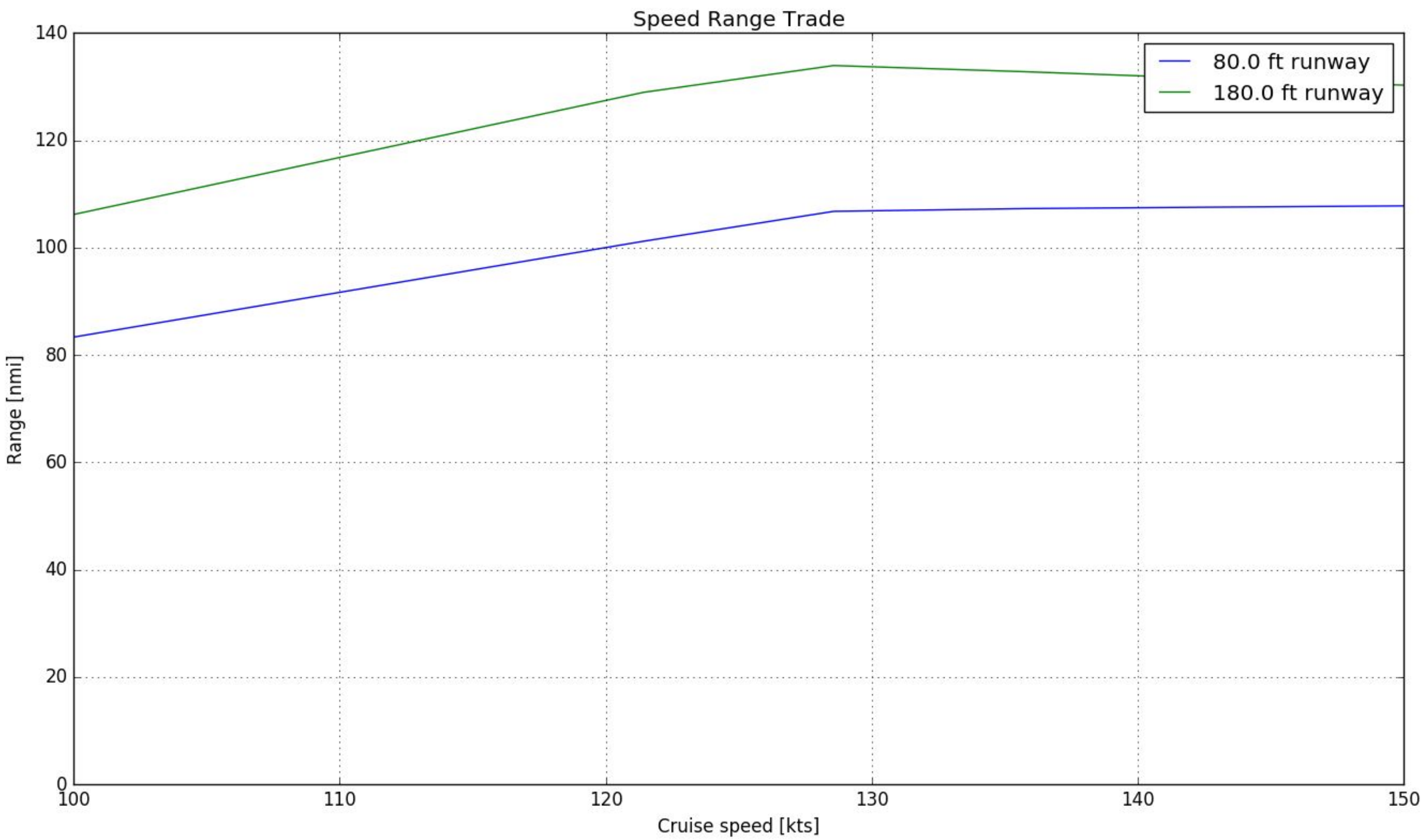
GPkit Performance Sweep



GPkit Performance Sweep



GPkit Performance Sweep



GPkit Mission Performance

Segment of Mission	Horizontal Velocity [kts]	Climb Rate [m/s]	C_L [-]	L/D [-]	Thrust [N]	T/W [-]	Battery Power [kW]	Engine Power [kW]	Total Power [kW]
Takeoff	27	0	8.08	4.5	6250	0.52	161	180	309
Obstacle	86.41	31.1	0.70	20	4631	0.39	161	180	309
Climb	117.9	2.23	0.37	22	983	0.08	0	84.5	76
Cruise	120	0	0.36	22	998	0.08	0	84.5	76
Landing	27.83	0	6.70	3.8	5058	0.42	161	180	309
Reserves	93.79	0	0.59	20	891.8	0.07	0	60.0	56

GPkit Mission Performance (C_L)

Segment of Mission	Horizontal Velocity [kts]	Climb Rate [m/s]	C_L [-]	L/D [-]	Thrust [N]	T/W [-]	Battery Power [kW]	Engine Power [kW]	Total Power [kW]
Takeoff	27	0	8.08	4.5	6250	0.52	161	180	309
Obstacle	86.41	31.1	0.70	20	4631	0.39	161	180	309
Climb	117.9	2.23	0.37	22	983	0.08	0	84.5	76
Cruise	120	0	0.36	22	998	0.08	0	84.5	76
Landing	27.83	0	6.70	3.8	5058	0.42	161	180	309
Reserves	93.79	0	0.59	20	891.8	0.07	0	60.0	56

Max C_L occurs during takeoff, GPkit showed 8.08

GPkit Mission Performance (L/D)

Segment of Mission	Horizontal Velocity [kts]	Climb Rate [m/s]	C_L [-]	L/D [-]	Thrust [N]	T/W [-]	Battery Power [kW]	Engine Power [kW]	Total Power [kW]
Takeoff	27	0	8.08	4.5	6250	0.52	161	180	309
Obstacle	86.41	31.1	0.70	20	4631	0.39	161	180	309
Climb	117.9	2.23	0.37	22	983	0.08	0	84.5	76
Cruise	120	0	0.36	22	998	0.08	0	84.5	76
Landing	27.83	0	6.70	3.8	5058	0.42	161	180	309
Reserves	93.79	0	0.59	20	891.8	0.07	0	60.0	56

Reserves has different L/D because it can minimize energy w.r.t. speed

GPkit Mission Performance (Power)

Segment of Mission	Horizontal Velocity [kts]	Climb Rate [m/s]	C_L [-]	L/D [-]	Thrust [N]	T/W [-]	Battery Power [kW]	Engine Power [kW]	Total Power [kW]
Takeoff	27	0	8.08	4.5	6250	0.52	161	180	309
Obstacle	86.41	31.1	0.70	20	4631	0.39	161	180	309
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Landing	27.83	0	6.70	3.8	5058	0.42	161	180	309
Reserves	93.79	0	0.59	20	891.8	0.07	0	60.0	56

Battery power used to supplement turboshaft engine on takeoff, obstacle clearance, and landing

Landing Detail

Approach Angle

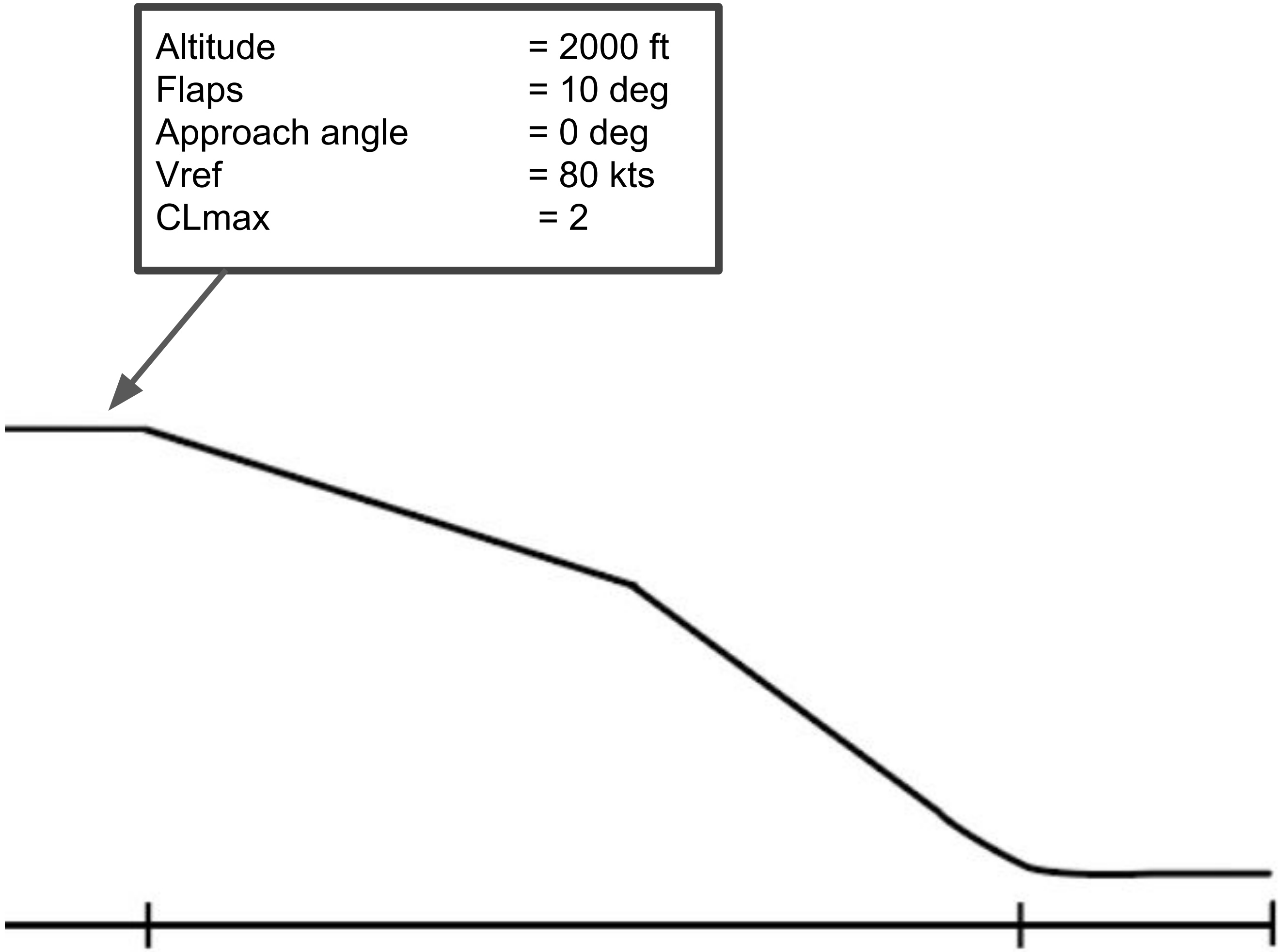
- Zero thrust approach angle: 16 deg
- Use outboard cruise motors to stabilize descent to 6 deg

Go Around

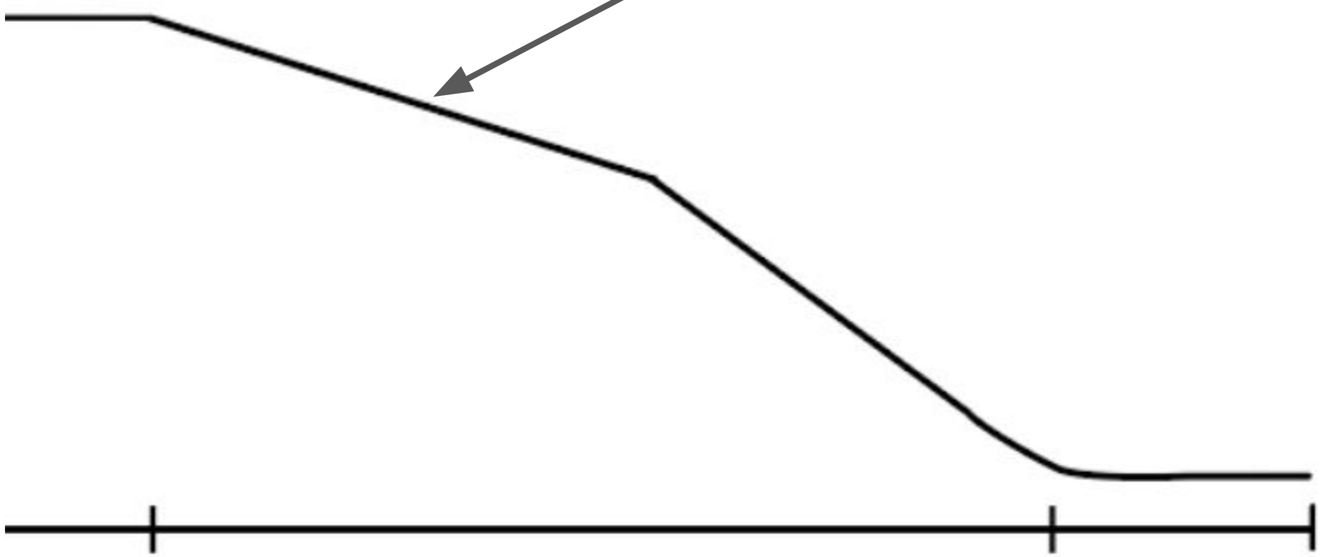
- The design is capable of go-around with flaps retracted
- Risk area for pilots (training to nose down to climb)
- Expected climb angle of 3 deg

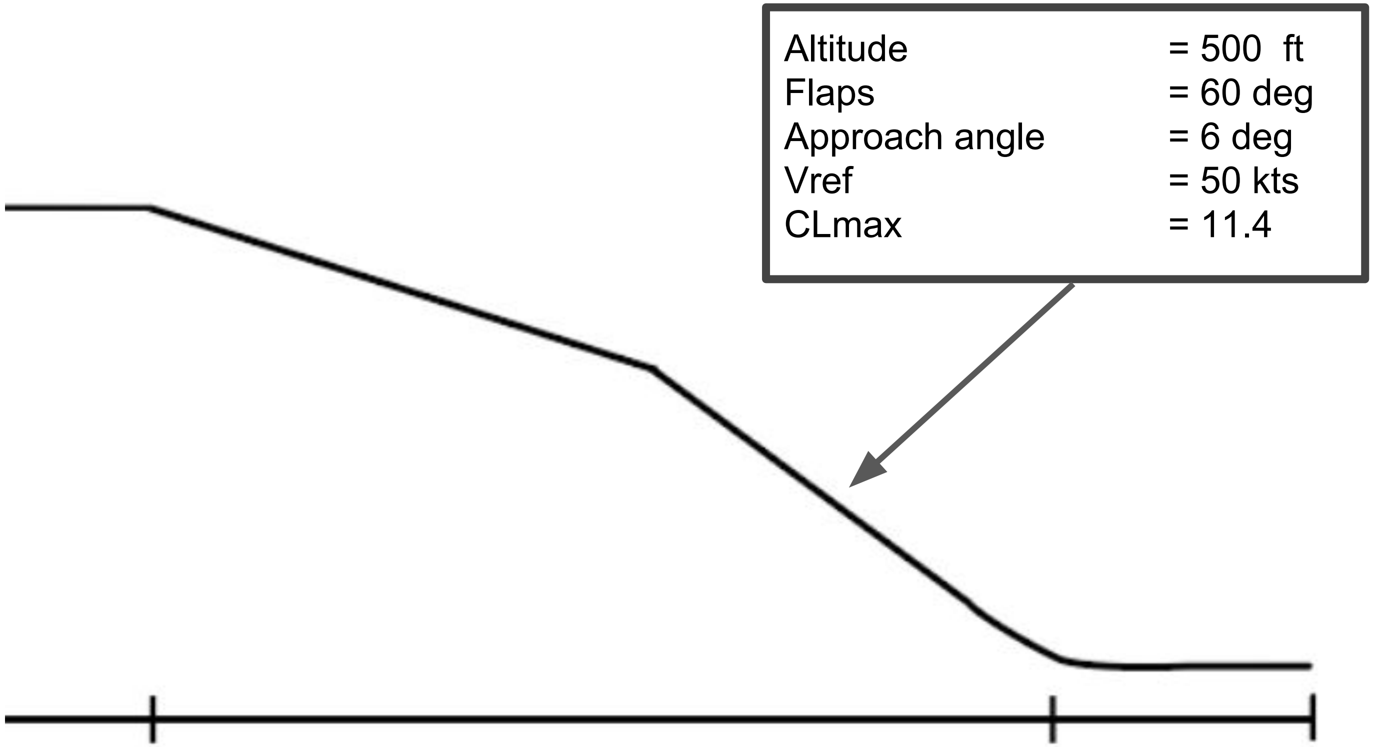
Full Blowing

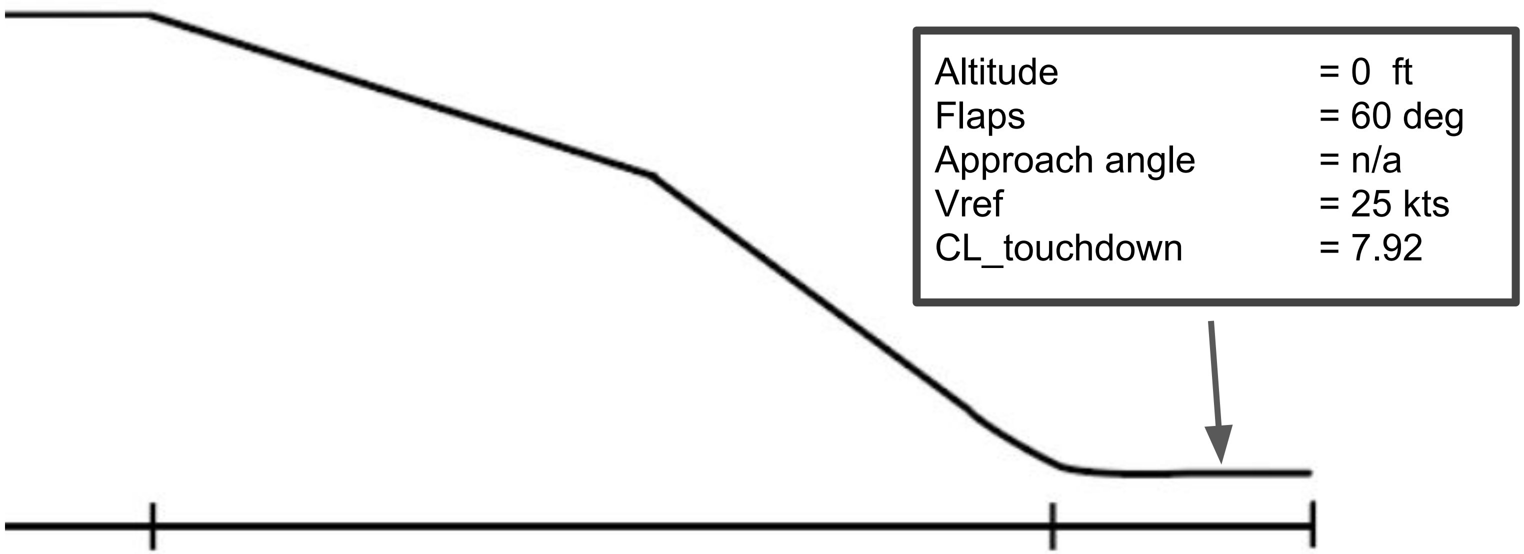
- Full thrust approach angle: 4 deg
- With flaps, full blowing still descends with nose up


Altitude = 2000 ft
Flaps = 10 deg
Approach angle = 0 deg
Vref = 80 kts
CLmax = 2

Altitude	= 800 ft
Flaps	= 30-40 deg
Approach angle	= 3 deg
Vref	= 50 kts
CLmax	= 4




Altitude = 500 ft
Flaps = 60 deg
Approach angle = 6 deg
Vref = 50 kts
CLmax = 11.4


Altitude = 0 ft
Flaps = 60 deg
Approach angle = n/a
Vref = 25 kts
CL_touchdown = 7.92

Landing Procedure

Altitude	Speed	Flaps	Maneuver
2000 ft	80 kts	10 deg	Descent
800 ft	50 kts	20-40 deg	Descent
500 ft	50 kts	60 deg	Blowing / Flare
0 ft	22 kts	60 deg	Touchdown

Outline

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Risk Areas

Known Risk Areas

- Integrated flap and blowing system
- Meeting calculated high lift performance
- Precision landing capability

Outline

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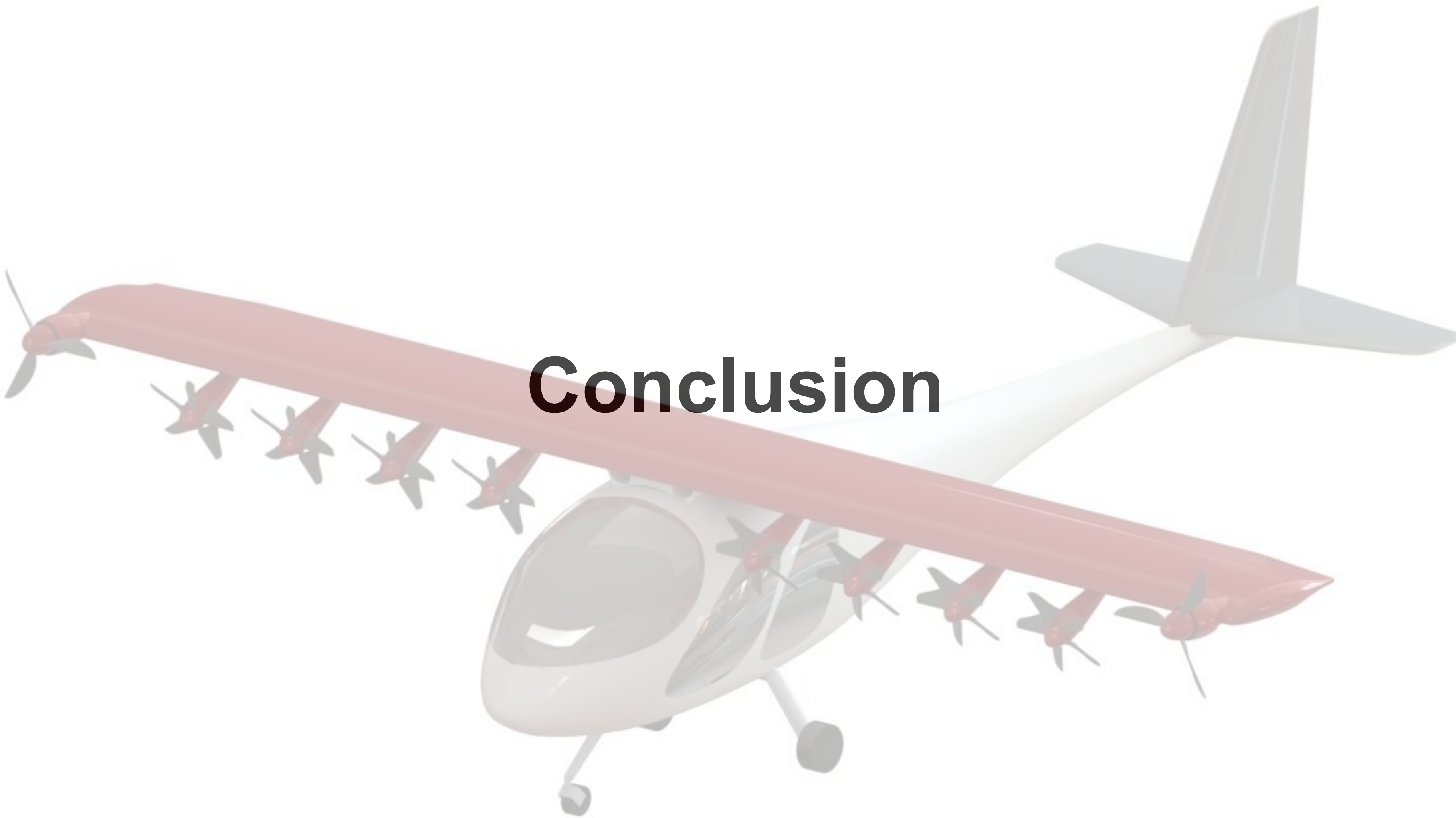
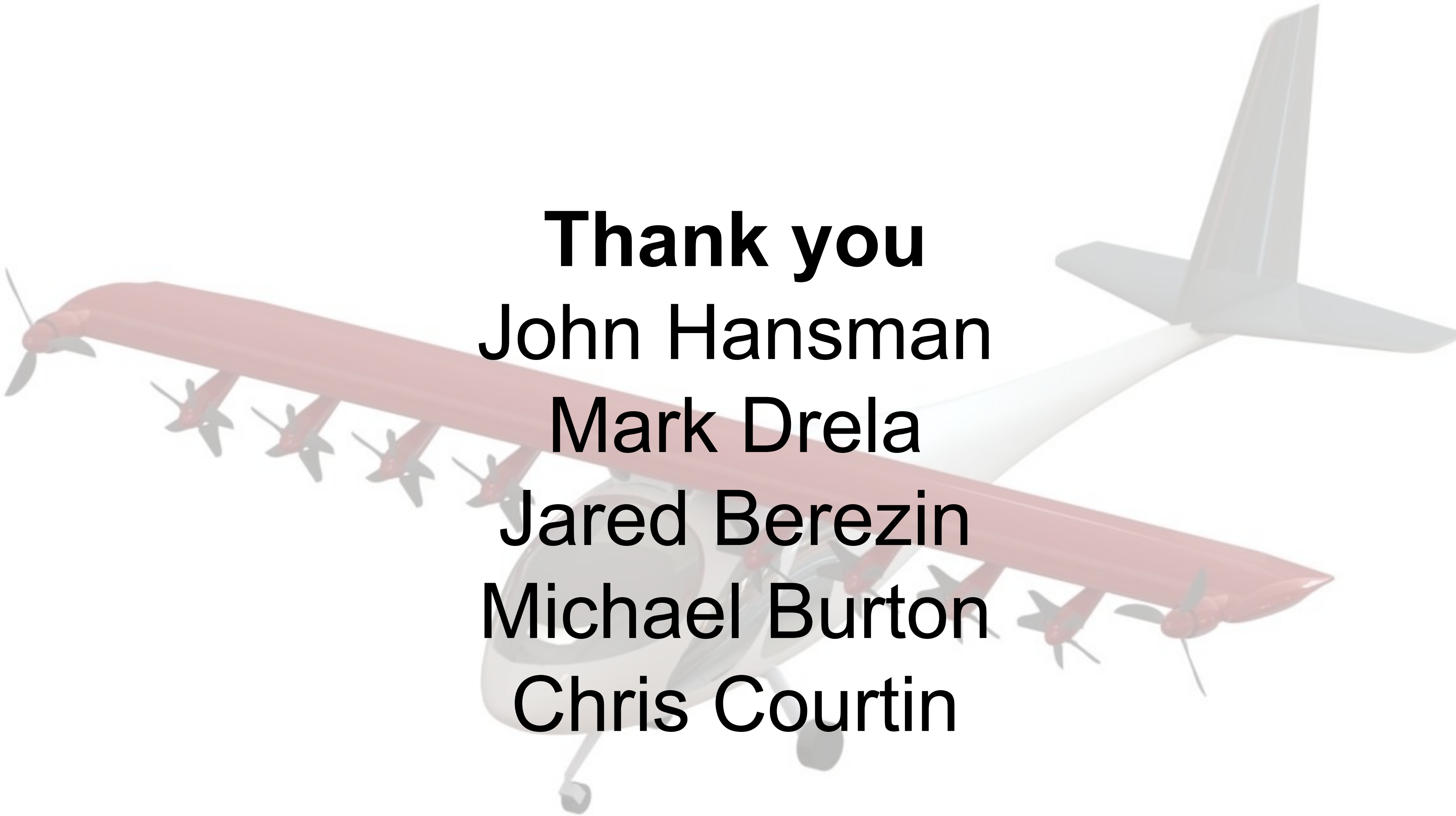
8. **Conclusion**



Conclusion

Conclusion

- 80 ft takeoff and landing distance
- Less certification risk than eVTOL designs
- Relies on existing technology



Thank you

John Hansman

Mark Drela

Jared Berezin

Michael Burton

Chris Courtin

Questions?

stolmit@mit.edu

Backup Slides

Payload Weight Requirement

Payload (includes pilot)	4 passengers and baggage

Interpretation: 205 lb + 20 lb per passenger → 900 lb payload

FAA AC 120-27E standard passenger weights:

- Average adult male: 205 lb
  - Includes winter clothing
- Personal items and carry-on bags: 20 lb

Payload Volume Requirement

Payload Volume	Able to accommodate medical litter or skis

Interpretation: 84" x 24" floor area available in cabin

- Medical litter requirement more difficult than ski requirement (< 84” L)
- Medevac II™ series Stokes-type litters
  - Most used helicopter rescue litters
  - 84" L x 24" W x 7" D

24”

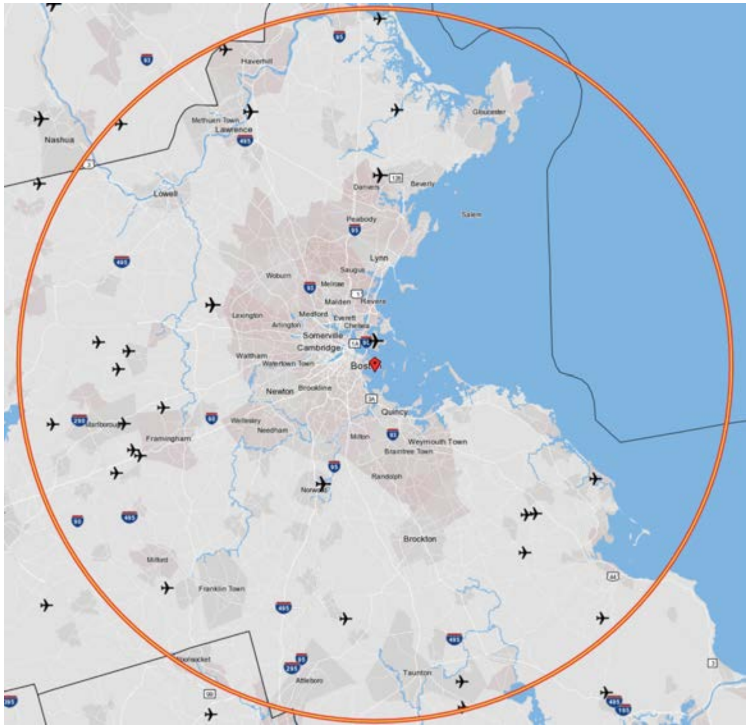
84”

Range and Reserve Requirement

Range	100 nmi with reserves

Interpretation: 100 nmi with 30 min reserve at normal cruise speed

Airports within 30 nmi of Boston



FAA FAR reserve fuel requirements:

- 91.167, flight in **IFR** conditions:
  - Fly to alternate + 45 min cruise
- 91.151, flight in **VFR** conditions:
  - 30 min cruise

Runway Requirement

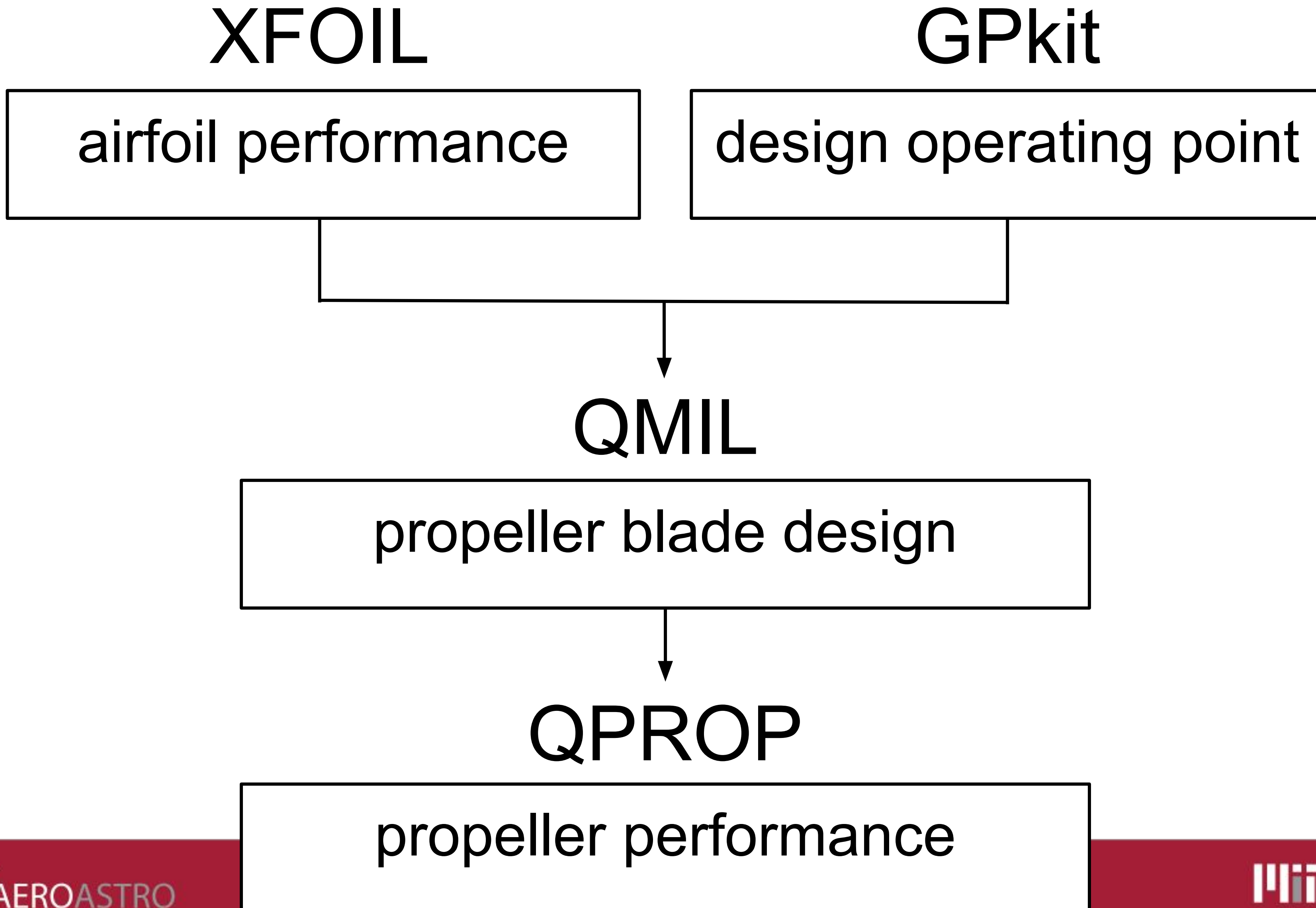
Runway	300 ft maximum 400 ft over 50 ft obstacle

Interpretation: 214 ft takeoff and landing ground roll

- 1.4 factor of safety

Driving requirement → capability of our aircraft that others don't have

Propeller Design



Known	Swept
n_{blades}, v_∞, T, R_{hub} CL, CD = f(alpha, Re) CL = f(span)	R_{tip} rpm

↓

QMIL

$c(r), \beta(r), Q, P, \eta = f(R_{tip}, rpm)$

↓

max $\eta = f(R_{tip})$

$c(r), \beta(r), Q, P, \eta, rpm = f(R_{tip})$

Motor Selection

- Sized for torque requirement + 10% margin

MAGicALL MAGiDRIVE integrated motors + controllers

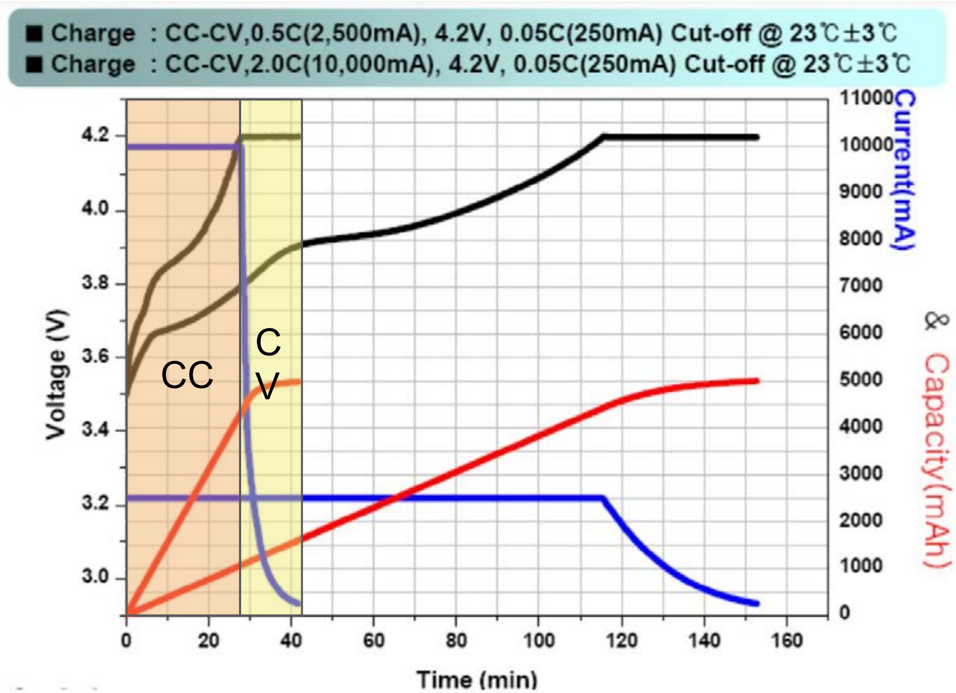
BASE MODEL	6	12	20	40	75	150	300
TORQUE RANGE, Nm	4 - 10	9 - 25	20 - 50	45 - 100	90 - 225	200 - 500	470 - 1000
POWER, kW (120s duration)	6	12	20	40	75	150	300
POWER, kW (continuous)	5	10	16	32	60	120	240
SPEED, RPM (maximum)	8,000	7,000	6,200	5,500	5,000	4,200	3,600
WEIGHT RANGE, kg	0.70 - 1.2	1.5 - 2.8	2.9 - 4.8	5.0 - 8.9	9.0 - 16.5	16.1 - 29.7	29.4 - 49.5
EFFICIENCY %, (typical)	90.5	91.5	92	92.5	93.5	94.5	95.5
OUTER DIAMETER, Inch	4.1	5.6	7.1	8.8	11.0	14.2	18.4
LENGTH RANGE, Inch	2.5 - 3.2	3.0 - 3.9	3.5 - 4.3	4.0 - 5.1	4.6 - 6.0	5.3 - 6.9	6.1 - 7.6

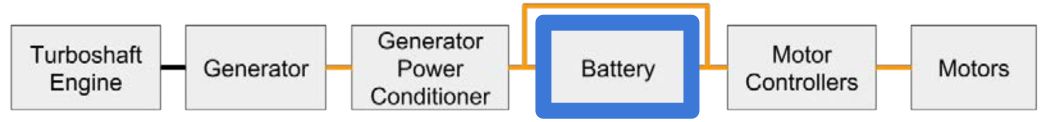
Powertrain Design Assumptions

Turboshaft Engine (IC), Fuel (F), and Fuel Tank (FT)	Battery (B) and Battery Pack (BP)	Motor / Generator (M) and Controllers (MC)
Engine specific power and thermal efficiency $P^{IC}_{\text{spec}_{\text{cont}}} = 2800 \text{ [W/kg]}$ $\eta^{IC} = 0.15$ Fuel specific energy $E^{F}_{\text{spec}} = 11,900 \text{ [Wh/kg]}$ Fuel tank packing efficiency of 90% by mass $m^{FT} = m^{F}/0.9$	Cell specific energy and power $E^{B}_{\text{spec}} = 140 \text{ [Wh/kg]}$ $P^{B}_{\text{spec}_{\text{cont}}} = 4200 \text{ [W/kg]}$ $P^{B}_{\text{spec}_{\text{max}}} = 7000 \text{ [W/kg]}$ Packing efficiency of 80% by mass $m^{BP} = m^{B}/0.8$	Motor / generator specific power $P^{M}_{\text{spec}_{\text{cont}}} = 5000 \text{ [W/kg]}$ $P^{M}_{\text{spec}_{\text{max}}} = 9000 \text{ [W/kg]}$ Motor / generator electrical efficiency $\eta^{M} = 0.9$ Controller specific power $P^{MC}_{\text{spec}_{\text{cont}}} \leq 11,800 \text{ [W/kg]}$ $P^{MC}_{\text{spec}_{\text{max}}} \leq 15,300 \text{ [W/kg]}$ Controller electrical efficiency $\eta^{MC} = 0.98$

Battery - Charging Operations

- Constant current - constant voltage (CC-CV)
  - CC at 2C rate until hit 4.2V, occurs at roughly 87% SOC
  - Then CV at 4.2V until drop below 0.05C
- Always operate in CV region
- **12.4 min recharge time**

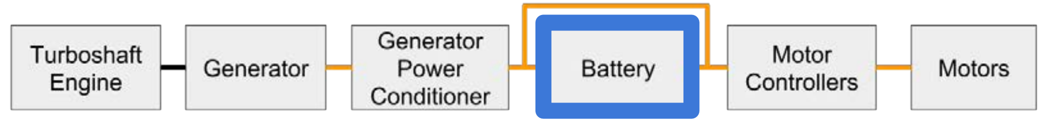




Battery - Thermal Management

- Normal operations
  - 2.7°C cell temperature rise during landing
    - Heat capacity of cell = 0.8 J/g/K
    - Cell temperature limit = 60°C
    - No convection, conduction
  - Allows for operation at up to **56.3°C** ambient
  - No active cooling required

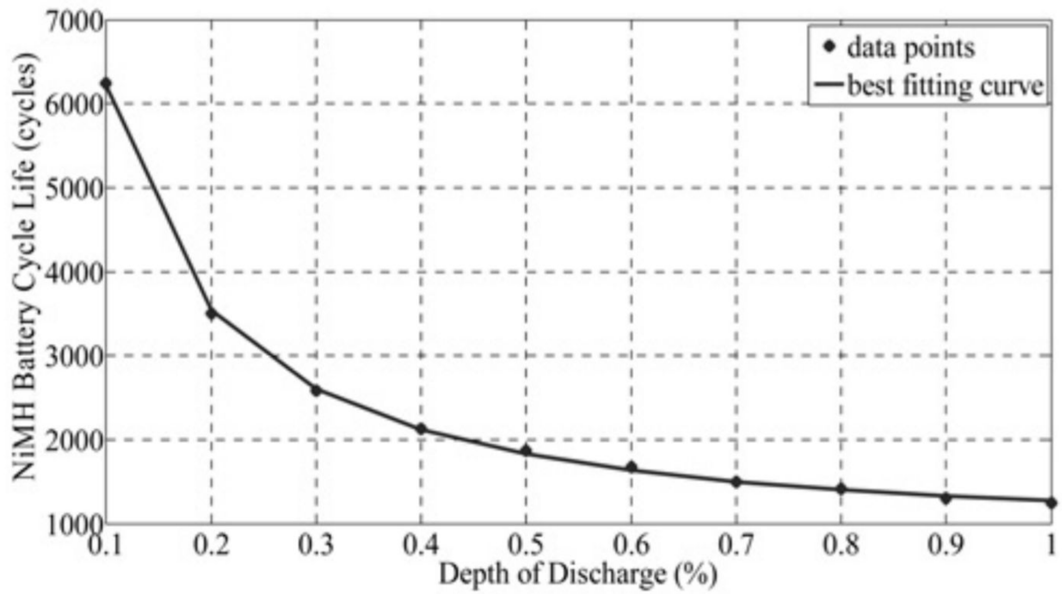
http://www.inforlab-chimie.fr/doc/document_fichier_279.pdf



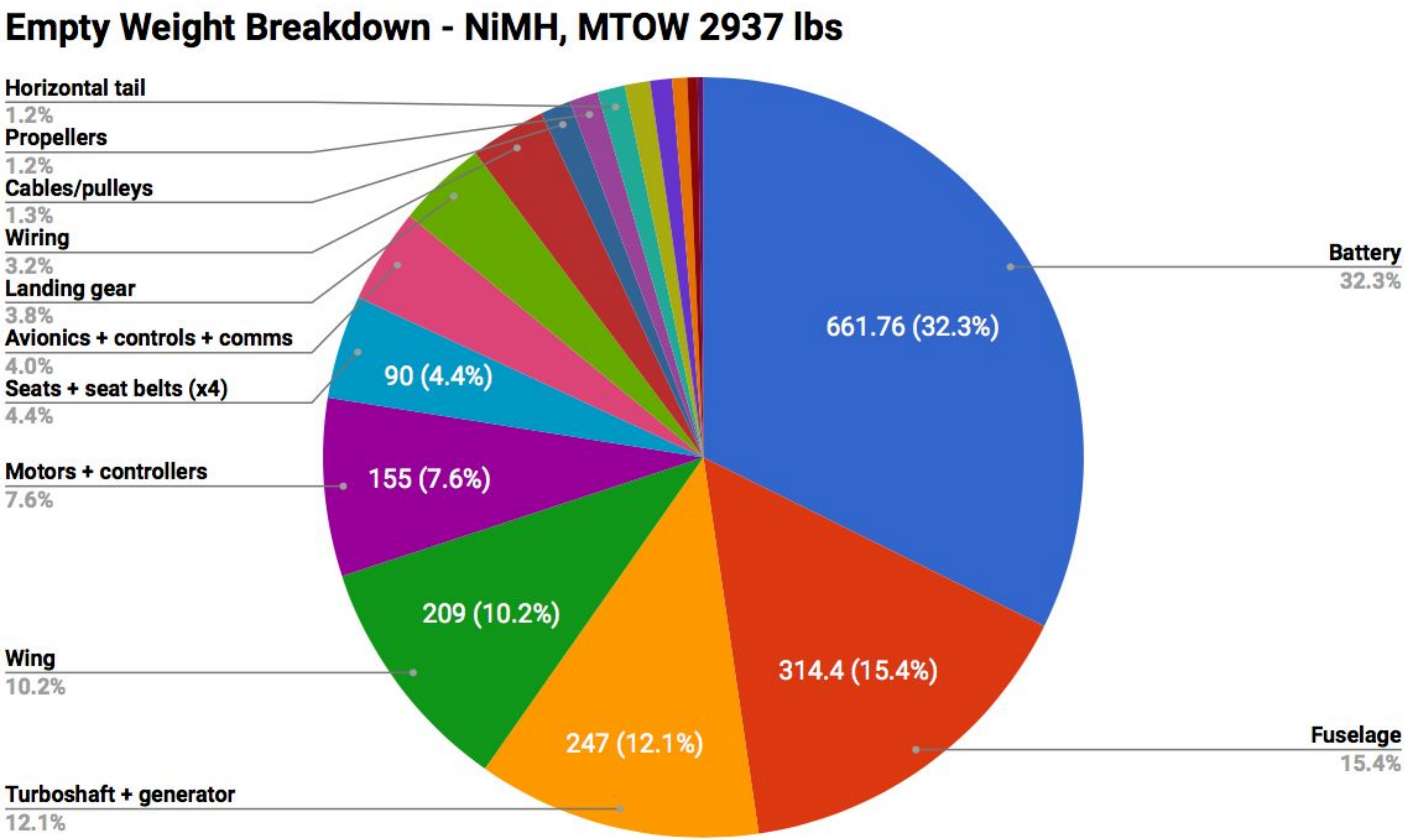
Ni-MH- Cycle Life

- Cell cycles at 3.8% DOD
  - Expect 5,000 to 10,000 cycles
  - Note: full battery capacity not needed

General Ni-MH Cycle Life vs DOD



https://www.researchgate.net/publication/280980003_Optimal_scheduling_of_virtual_power_plant_with_battery_degradation_cost


Empty Weight Breakdown - NiMH, MTOW 2937 lbs
Horizontal tail
1.2%
Propellers
1.2%
Cables/pulleys
1.3%
Wiring
3.2%
Landing gear
3.8%
Avionics + controls + comms
4.0%
Seats + seat belts (x4)
4.4%
Motors + controllers
7.6%
Wing
10.2%
Turboshaft + generator
12.1%
Battery
32.3%
Fuselage
15.4%
661.76 (32.3%)
314.4 (15.4%)
247 (12.1%)
209 (10.2%)
155 (7.6%)
90 (4.4%)