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Sizing and Optimization of a Lift-Plus-Cruise Urban Air Mobility Concept with Electrified Propulsion

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Webcast for the
NASA Engineering and Safety Center Flight Mechanics Technical Discipline Team

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(August 2018 – present)

Research Engineer II
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Ph.D., Aerospace Engineering (Dec 2015)
Georgia Institute of Technology

M.S., Aerospace Engineering (Jul 2011)
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B.Tech., Mechanical Engineering (May 2009)
National Institute of Technology Trichy, India

Professional Memberships

- AIAA Associate Fellow (class of 2023)
- AIAA Aircraft Design Technical Committee
- AIAA Modeling & Simulation Technologies Technical Committee

Aviation

- Private Pilot, Airplane, Single-Engine, Land (Mar 2013 – present)
- Airplane owner (Jan 2022 – present)

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Vehicle Systems, Dynamics, and Design Laboratory (VSDDL)

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- VSDDL research focuses on sizing, performance and stability & control analysis, and flight simulation
- Developed the PEACE aircraft sizing framework, applicable to vehicles using wing-borne, rotor-borne, and buoyant lift or combinations thereof
- Developed the MADCASP S&C analysis and flight simulation framework with NASA funding; aimed at analysis of novel configurations
- Developed cockpit flight simulators to enable human-in-the-loop flight simulation research for Advanced Air Mobility (AAM) concepts

VSDDL

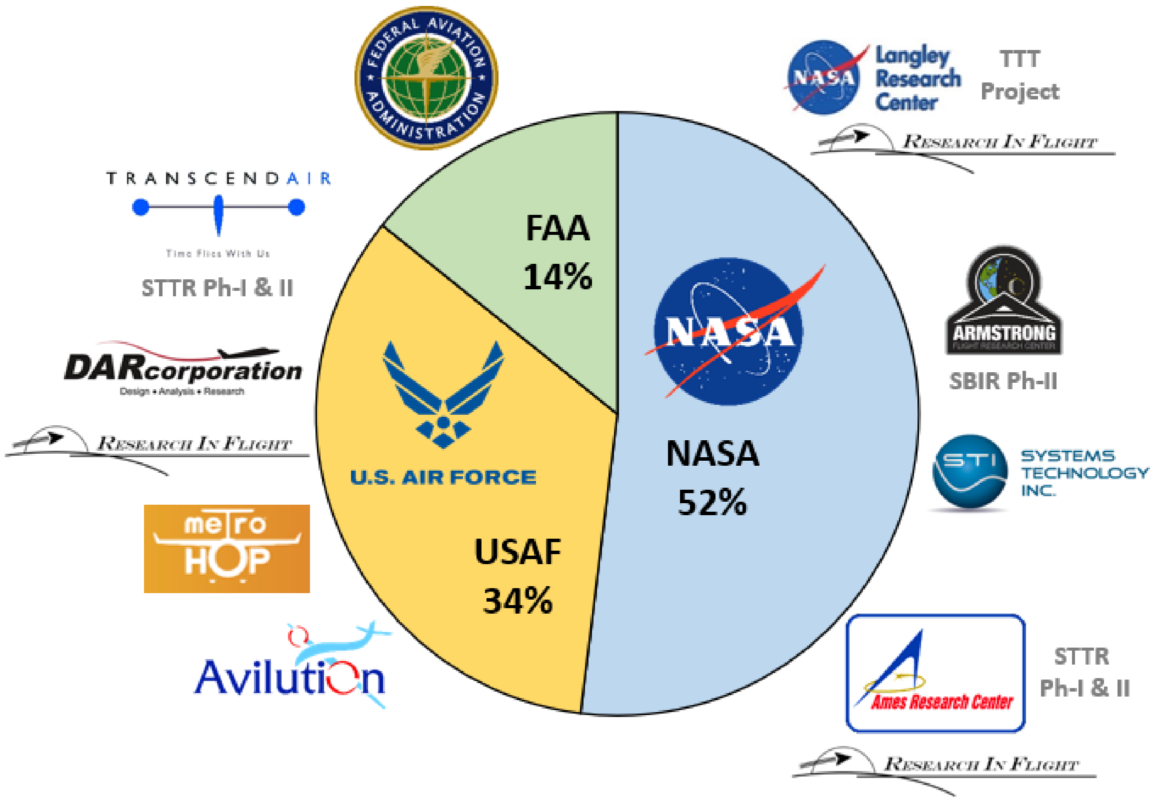
“Vehicle”
- Conventional & Unconventional

“Systems”
- Sizing & analysis of key systems

“Dynamics”
- Flight simulation, S&C analyses

“Design”
- Capture impacts of above on vehicle design

Cumulative external funding flowing to VSDDL @ AU from Aug 2018 – present: $1.5M+



Research Motivation – A Number of Challenges

- Plenty of new flight vehicles under development / testing
  - Many supporting the Urban Air Mobility ConOps
- Sizing & performance analysis challenges
  - Unconventional configurations
  - Electrified propulsion systems (all-, hybrid-, turbo-electric)
  - Distributed propulsion systems
  - Higher aero-propulsive coupling
- Stability & control challenges
  - Over-actuated systems
  - Dynamic stability characteristics?
  - Flight control design for Simplified Vehicle Operations (SVO)
  - The evolving role of the human pilot/operator
- The above influence research efforts at the Vehicle Systems, Dynamics, and Design Laboratory (VSDDL)

Just a small sample. Not an exhaustive list


Joby Aviation S4


Archer Maker


Beta Technologies ALIA

Wisk Aero Cora



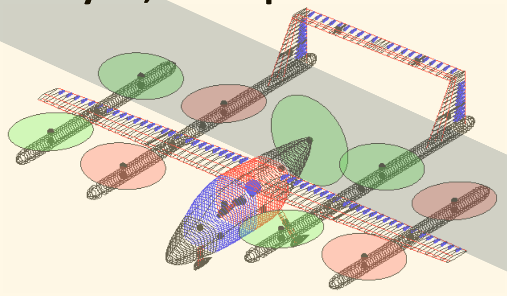
NASA X-57 Maxwell


Electra eSTOL

Images: evtol.news, electra.aero, businessinsidercom

VSDDL Vision: An R&D “Pipeline” for Next-Gen Concepts

Vehicle sizing, performance analysis, and optimization

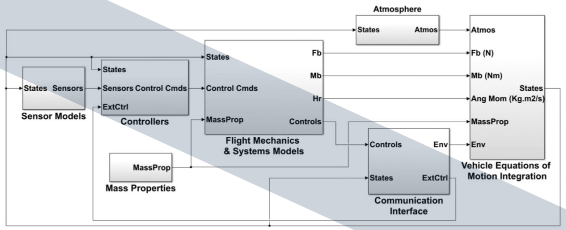


Parametric Energy-based Aircraft Configuration Evaluator (PEACE)

Developed internally at VSDDL; aimed at facilitating sizing and performance analysis of novel aircraft and propulsion system architectures

Webcast #1, Feb 22, 2023, 1:00 pm EST

S&C analysis, flight control system architecture design & optimization

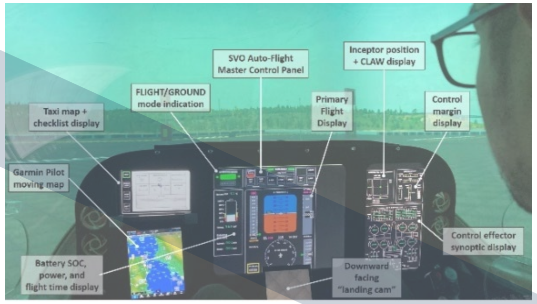


Modular Aircraft Dynamics and Control Algorithm Simulation Platform (MADCASP)

Developed with funding from NASA Langley Research Center under Transformational Tools and Technologies (TTT) Project

Webcast #2, Mar 1, 2023, 1:00 pm EST

Flight simulation model development; human-in-the-loop simulations

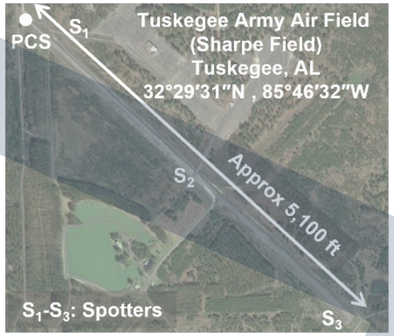


VSDDL Flight Simulators

Developed in-house for studying Simplified Vehicle Operations (SVO)

Webcast #3, Mar 8, 2023, 1:00 pm EST

Subscale prototype development & piloted flight tests



VSDDL Vision: An R&D "Pipeline" for Next-Gen Concepts

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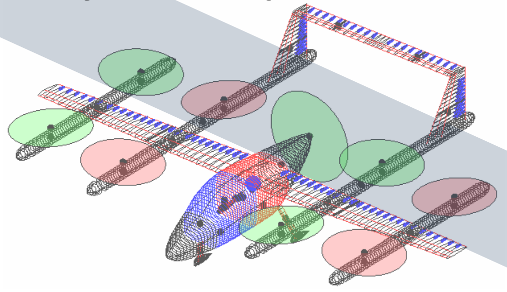
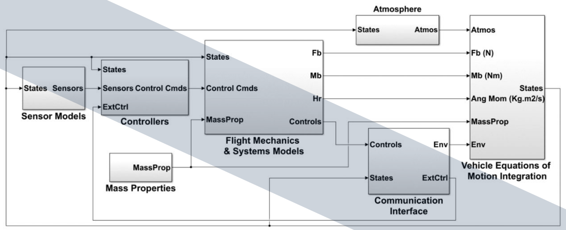
Vehicle sizing, performance analysis, and optimization



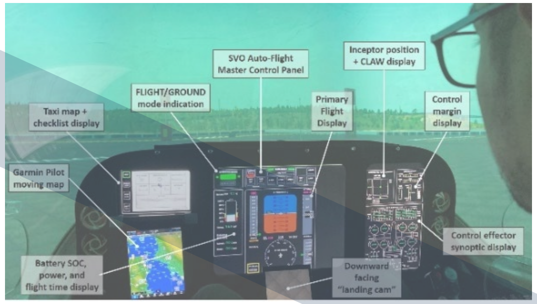
Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

S&C analysis, flight control system architecture design & optimization



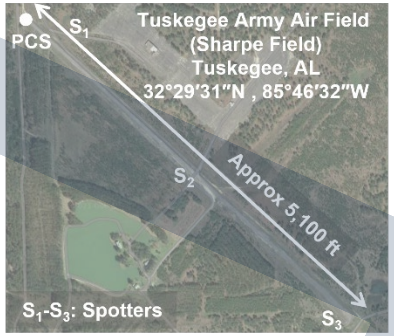
Comer, A. and Chakraborty, I., **"Total Energy Flight Control Architecture Optimization for a Lift-Plus-Cruise Aircraft,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0399

Flight simulation model development; human-in-the-loop simulations



Chakraborty et al., **"Flight Simulation Based Assessment of Simplified Vehicle Operations for Urban Air Mobility,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0400

Subscale prototype development & piloted flight tests



Starting with Some Familiar "Energy" Concepts

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Rate of energy addition by propulsion system → $\underline{T}^T\underline{V}$

Rate of energy dissipation by drag forces → $\underline{D}^T\underline{V}$

Potential energy → Wh

Kinetic energy → $\frac{1}{2}\frac{W}{g}V^2$

$$\underline{T}^T\underline{V} + \underline{D}^T\underline{V} = \frac{d}{dt}\left(Wh + \frac{1}{2}\frac{W}{g}V^2\right)$$

- **Thrust aligned with velocity (by assumption)**
- **Drag opposite to velocity (by definition)**

$$\frac{TV - DV}{W} = \frac{d}{dt}\left(h + \frac{V^2}{2g}\right) = \frac{dH_e}{dt} = P_s$$

- The assumption that thrust is aligned with velocity
  - May be reasonable for fixed-wing aircraft at low AOA
  - Not accurate for low-speed flight at higher AOA
  - Not valid when a significant thrust component is orthogonal to the flight path
    - e.g., when there is rotor-borne lift (conventional helicopters, transitioning VTOLs)
- For hovering flight, both sides of the equation go to 0
  - Not useful for assessing hover power requirements
- No explicit consideration of rotational equilibria (i.e., "trim"), which affect performance and power required

➢ **Consider force and moment equilibria in addition to the power balance shown here**

➢ **Generalize these concepts for vehicles using wing-borne, rotor-borne, or buoyant lift or combinations thereof**

Generalized Vehicle Performance Modeling Approach

- Translational equations of motion in wind axes:

$$\underline{\dot{V}}^{[\mathcal{W}]} = \frac{1}{m}\underline{F}^{[\mathcal{W}]} - \underline{\tilde{\omega}}^{[\mathcal{W}]}\underline{V}^{[\mathcal{W}]}$$

- Consider motion in the vertical (x-z) plane; separate out gravity forces

$$\dot{V} = \frac{1}{m}F_{x_A} - g\sin\gamma, \quad -V\dot{\gamma} = \frac{1}{m}F_{z_A} + g\cos\gamma$$

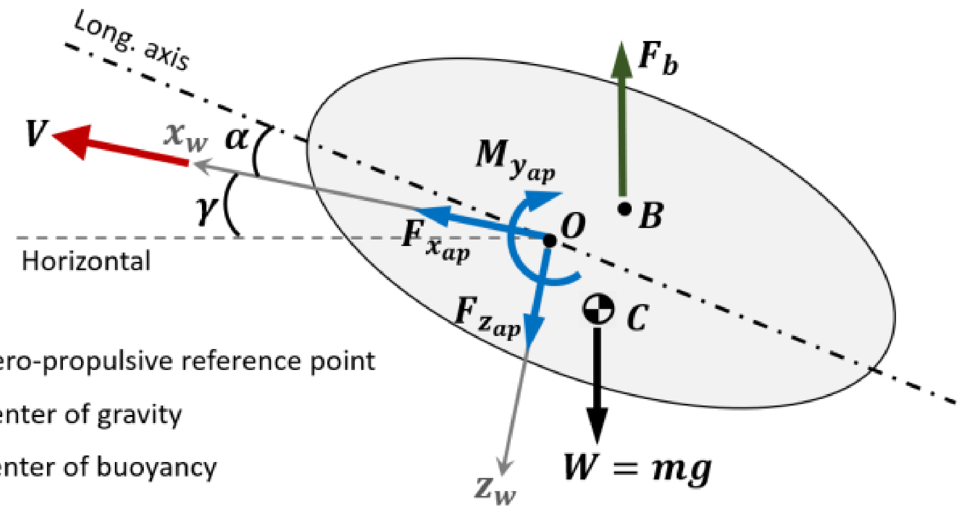
Net air reactions

- Some algebra:

$$\frac{V}{g}\dot{V} = \frac{1}{mg}F_{x_A}V - V\sin\gamma = \frac{F_{x_A}V}{W} - \dot{h}$$

$$\frac{F_{x_A}V}{W} = \frac{d}{dt}\left(h + \frac{V^2}{2g}\right) = \frac{dH_e}{dt} = P_s$$

Rate of change of energy height, i.e., specific excess power



O: aero-propulsive reference point

C: center of gravity

B: center of buoyancy

Net air reactions →

$$F_{x_A} = F_{x_{ap}} + F_{b_x}$$

$$F_{z_A} = F_{z_{ap}} + F_{b_z}$$

← **Buoyancy components**

Aero-propulsive force components do not need to be split into "thrust" and "drag" components

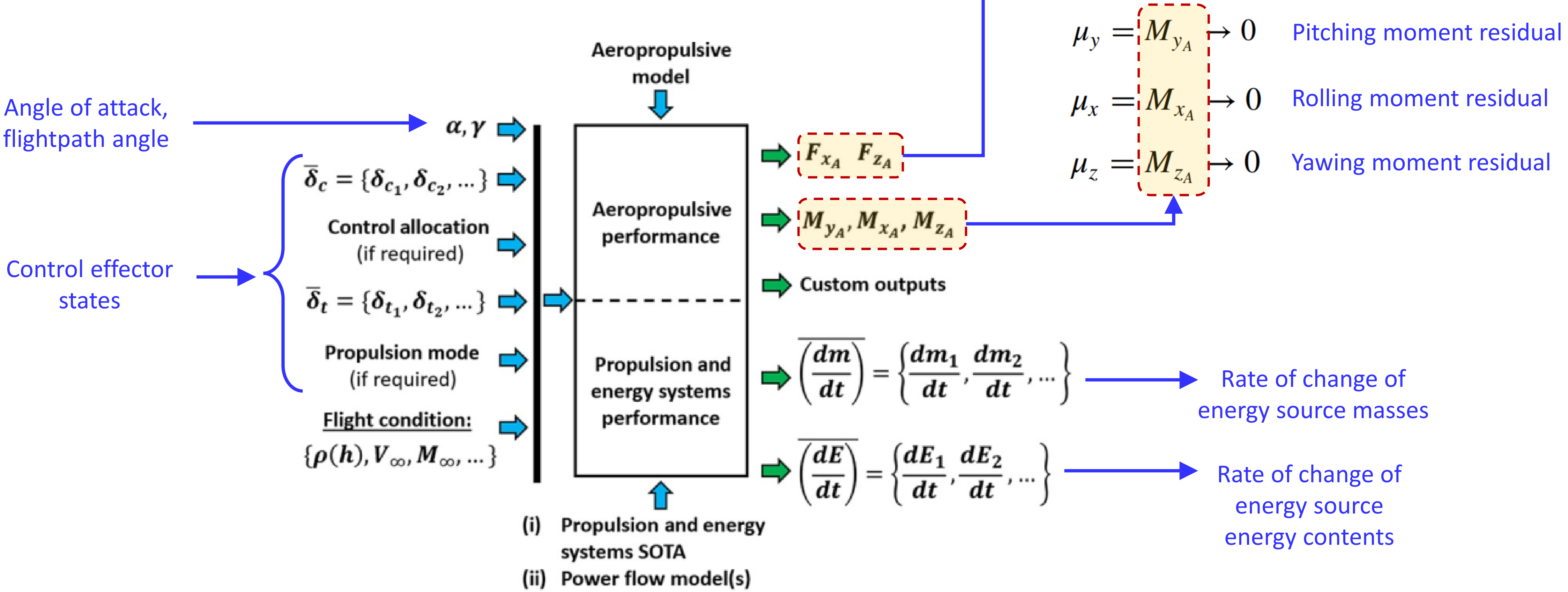
Chakraborty, I. and Mishra, A.A., "A Generalized Energy-Based Flight Vehicle Sizing and Performance Analysis Methodology," AIAA Journal of Aircraft, Volume 58, No 4, pp 762-780, July 2021, DOI: 10.2514/1.C036101 (also AIAA-2021-1721 @ AIAA SCITECH 2021, Best Paper Award from AIAA Aircraft Design TC)

Aero-Propulsive Performance Model (APPM)

- The APPM **functional form** is **invariant** to vehicle configuration and propulsion system architecture
- Different types of aero-propulsive and propulsion system models can be incorporated

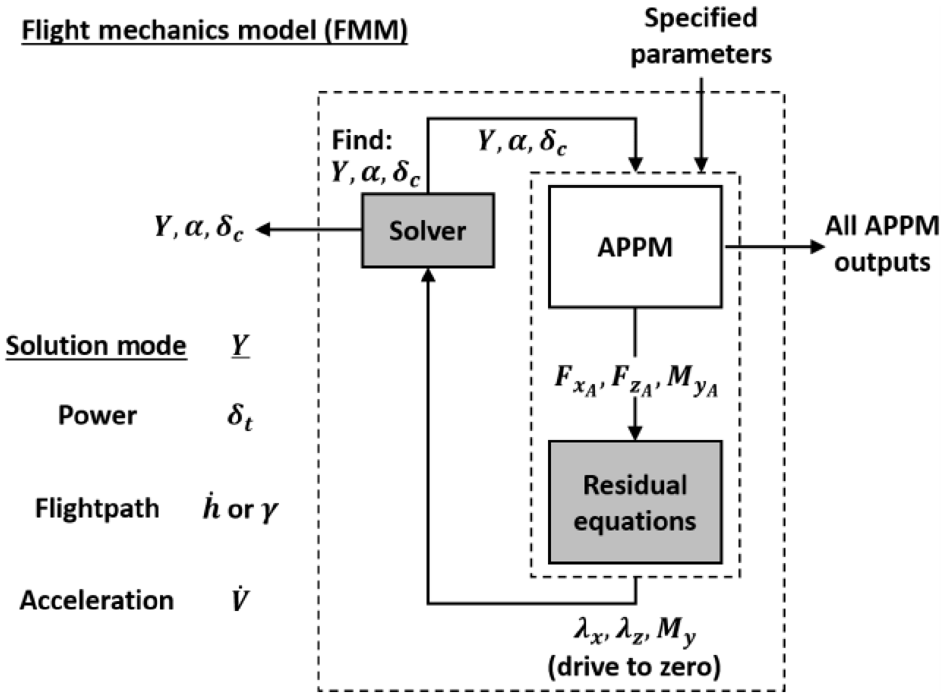
$$\lambda_x = \frac{1}{m} F_{x_A} - g \sin\gamma - \dot{V} \rightarrow 0$$ Axial force residual

$$\lambda_z = \frac{1}{m} F_{z_A} + g \cos\gamma + V\dot{\gamma} \rightarrow 0$$ Normal force residual



Flight Mechanics Model (FMM)

- The APPM is solved within the **Flight Mechanics Model (FMM)**
- Solution modes for FMM
  - **Power mode:** How much power is needed to sustain a given flight condition?
  - **Flightpath mode:** For a given power setting, what is the equilibrium flightpath angle?
  - **Acceleration mode:** For a given power setting, what is the resulting acceleration?
  - **Trim mode:** Like power mode, but considers all three rotational axes, not just pitch axis
- Additional sub-modes may exist for transitioning/VTOL aircraft (e.g., vertical flight versus forward flight)



All solution modes

$$\lambda_x = \frac{1}{m} F_{x_A} - g \sin\gamma - \dot{V} \rightarrow 0$$

$$\lambda_z = \frac{1}{m} F_{z_A} + g \cos\gamma + V\dot{\gamma} \rightarrow 0$$

$$\mu_y = M_{y_A} \rightarrow 0$$

Trim mode

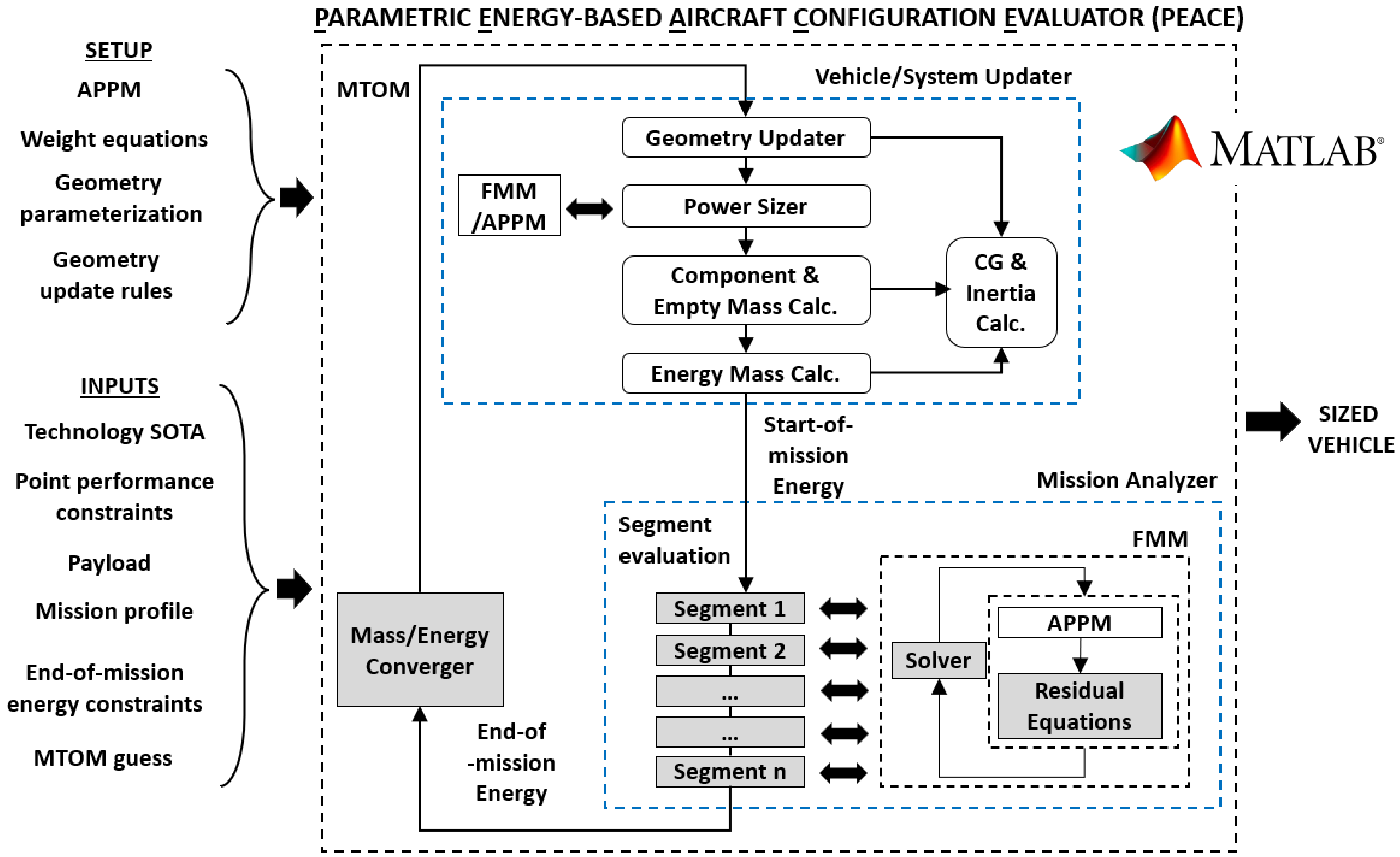
Also enforces:

$$\mu_x = M_{x_A} \rightarrow 0$$

$$\mu_z = M_{z_A} \rightarrow 0$$

Parametric Energy-based Aircraft Configuration Evaluator (PEACE)

- Energy-based sizing framework; handles concepts using wing-borne, rotor-borne, and/or buoyant lift
- Energy sources are all treated in an equivalent manner; can handle electric, hybrid, and conventional propulsion
- Propulsion components are sized by an explicit *power sizing* analysis
- Energy requirements are computed by explicitly *trimming* the aircraft at each point within each discretized mission segment



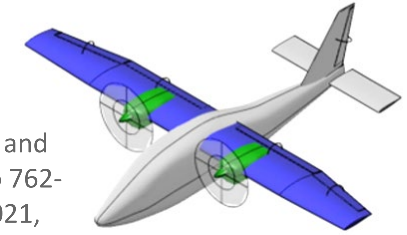
Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022, Best Paper Award from AIAA Electrified Aircraft Technology TC)

Some Prior Studies and Papers using the PEACE Framework

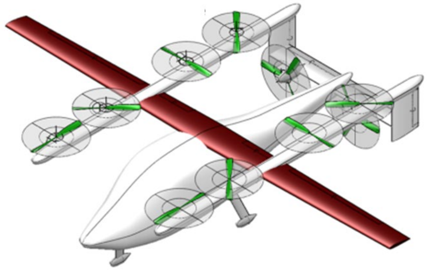
PEACE underlying methodology and applications to sizing **(i)** conventional fixed-wing GA aircraft, **(ii)** all-electric lift-plus-cruise e-VTOL, and **(iii)** hybrid lift airship

Chakraborty, I. and Mishra, A.A., "A Generalized Energy-Based Flight Vehicle Sizing and Performance Analysis Methodology," AIAA Journal of Aircraft, Volume 58, No 4, pp 762-780, July 2021, DOI: 10.2514/1.C036101 (also AIAA-2021-1721 @ AIAA SCITECH 2021, Best Paper Award from AIAA Aircraft Design TC)

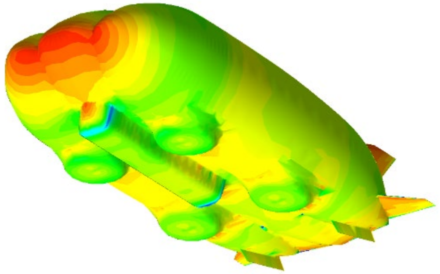
Fixed-wing GA Aircraft



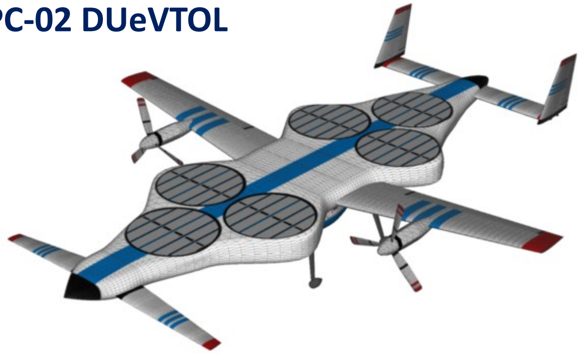
LPC-01 Pushpak



Hybrid Lift Airship



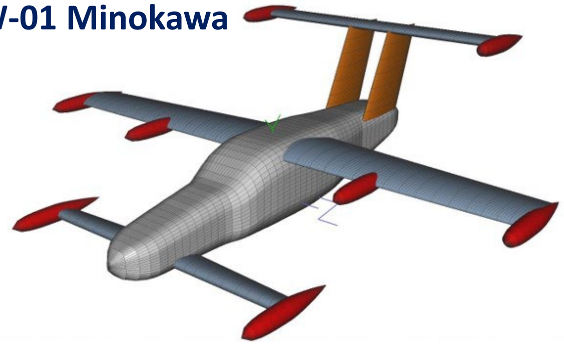
LPC-02 DUeVTOL



Sizing of a ducted fan **lift-plus-cruise** VTOL configuration with **all-electric** and **hybrid-electric** propulsion architectures

Chakraborty, I., Mishra, A.A., van Dommelen, D., and Anemaat, W.A.J., "Design and Sizing of an Electrified Lift-Plus-Cruise Ducted Fan Aircraft," AIAA Journal of Aircraft, Article in Advance, Nov 30, 2022, DOI: 10.2514/1.C036811 (also AIAA-2022-1516 @ AIAA SCITECH 2022)

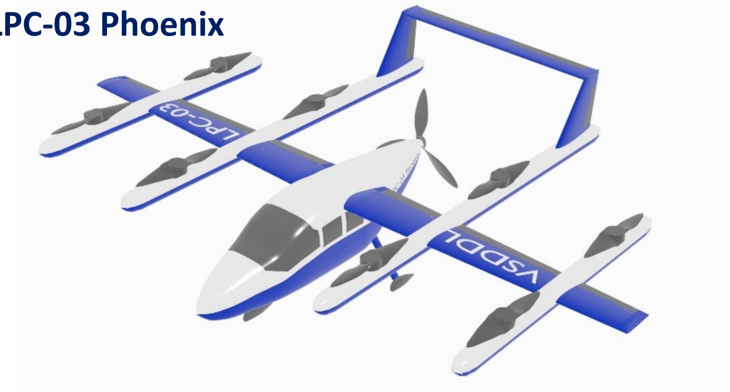
TW-01 Minokawa



Sizing of a **tilt-wing** VTOL configuration with **all-electric** and **hybrid-electric** propulsion architectures

Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Tilt-Wing Aircraft with All-Electric and Hybrid-Electric Propulsion," AIAA Journal of Aircraft, Article in Advance, August 15, 2022, DOI: 10.2514/1.C036813 (also AIAA-2022-1515 @ AIAA SCITECH 2022)

LPC-03 Phoenix

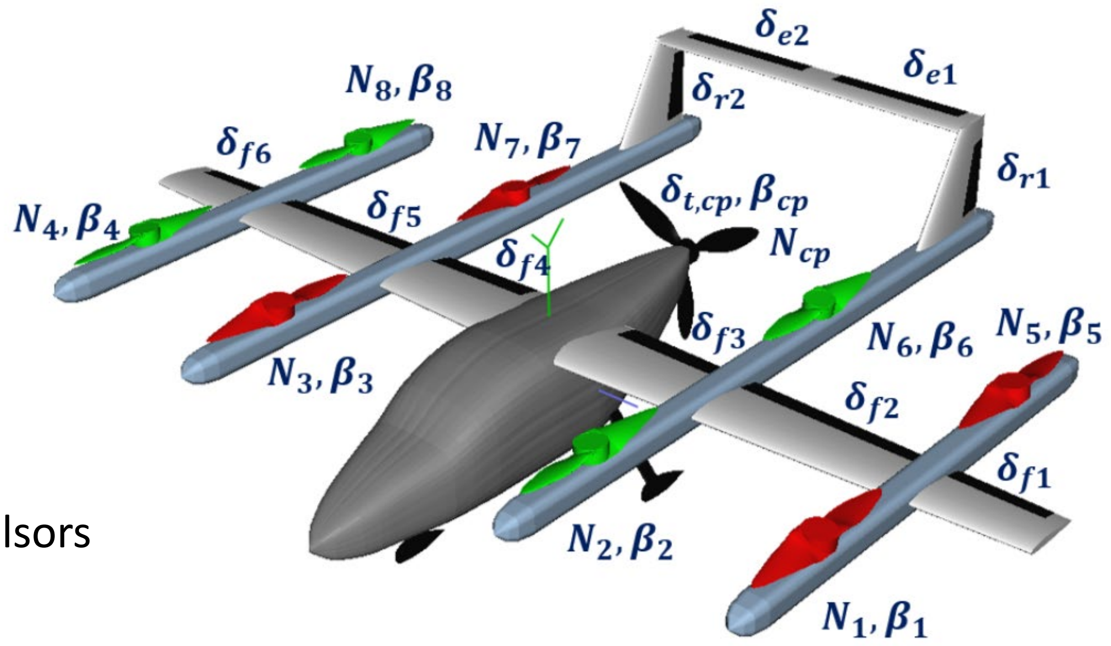


Sizing of a **lift-plus-cruise** VTOL configuration with **all-electric**, **hybrid-electric**, and **turbo-electric** propulsion architectures

Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022, Best Paper Award from AIAA Electrified Aircraft Technology TC)

Lift-Plus-Cruise (LPC) Urban Air Mobility (UAM) Concept with Electrified Propulsion

- "Lift-Plus-Cruise" – separate propulsors for vertical thrust ("lift") and forward thrust (for cruise)
  - Advantage: Simpler aerodynamically than vectored thrust (tilt-wing and tilt-rotor) configurations
  - Disadvantage: In cruise flight, the lift propulsors are inactive, thus "dead-weight" and drag penalties
- Attitude control:
  - Vertical flight mode: using differential thrust of lift propulsors
  - Forward flight mode: using control surfaces
  - Control allocation and blending during transition
- If you cannot trim, you cannot fly!
  - Control allocation and "trim" considerations (both nominal and off-nominal flight conditions) are part of the sizing approach in PEACE
  - This will have a major impact on power sizing of propulsion system components!



#	Symbol	Description	Unit
1-3	$\delta_{f1}, \delta_{f2}, \delta_{f3}$	Flaperon, left wing, out-/mid-/inboard	deg
4-6	$\delta_{f4}, \delta_{f5}, \delta_{f6}$	Flaperon, right wing, in-/mid-/outboard	deg
7, 8	δ_{e1}, δ_{e2}	Left, right elevator	deg
9, 10	δ_{r1}, δ_{r2}	Left, right rudder	deg
11	$\delta_{t,cp}$	Cruise propeller throttle setting	–
12	β_{cp}	Cruise propeller pitch	deg
13	N_{cp}	Cruise propeller RPM	RPM
14-21	$N_1 - N_8$	Lift propeller RPMs	RPM
22-29	$\beta_1 - \beta_8$	Lift propeller pitch	deg

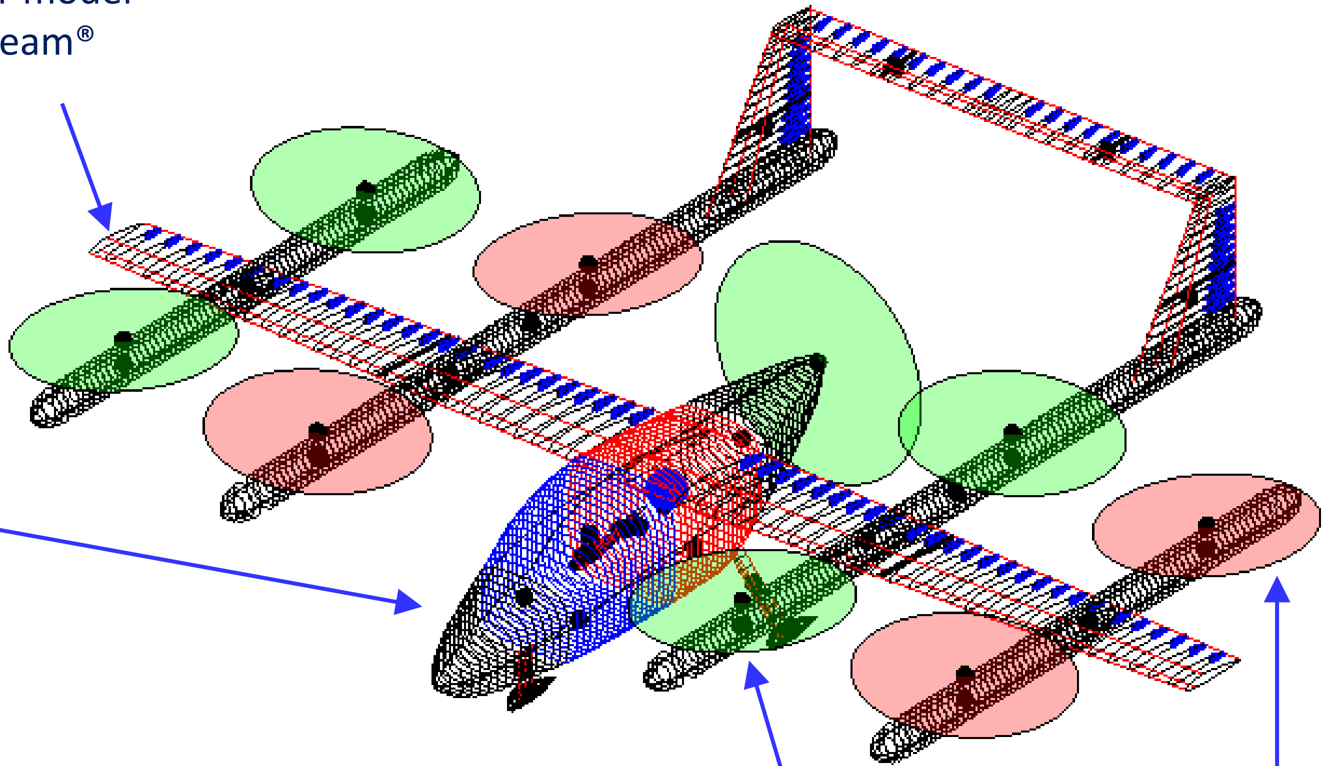
Parametric Geometry Model & Aero-Propulsive Analysis Approach

Lifting surfaces: All lifting surfaces are discretized into strips. Strip sectional aero, downwash reduced order model generated using FlightStream®

Wireframe geometry model of aircraft within PEACE (MATLAB)

Geometry update rules:
These rules are specified during problem setup. They govern how the geometry of a component updates during sizing iterations, how components are located or mounted relative to other components, etc.

Non-strip geometry:
Loads are analyzed separately using FlightStream® to create lookup tables that are queried during sizing



Mass properties:
Mass: component weight equations for GA aircraft, plus calculated weights of propulsion & energy system components
CG & inertia: computed per component; summed appropriately

Propulsors: Modeled using a blade element momentum theory model coupled with a Pitt-Peters inflow model

Note:
For further details regarding modeling approach, see:
Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044

Geometry Definition and Geometry Import/Export

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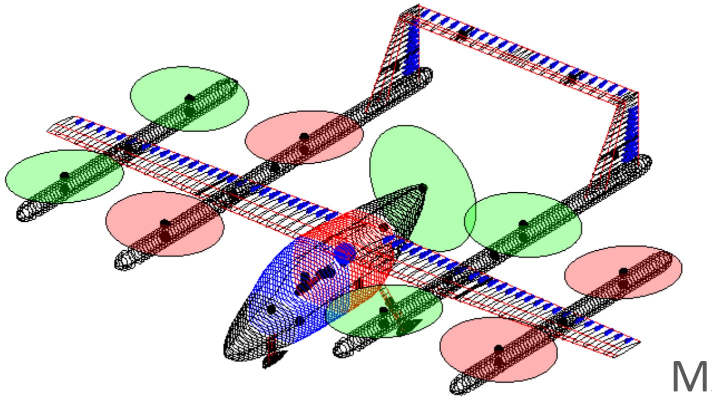
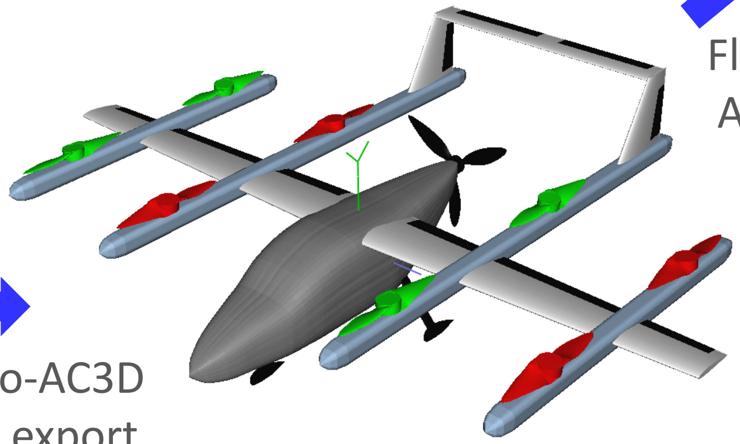
PEACE wireframe geometry (MATLAB)



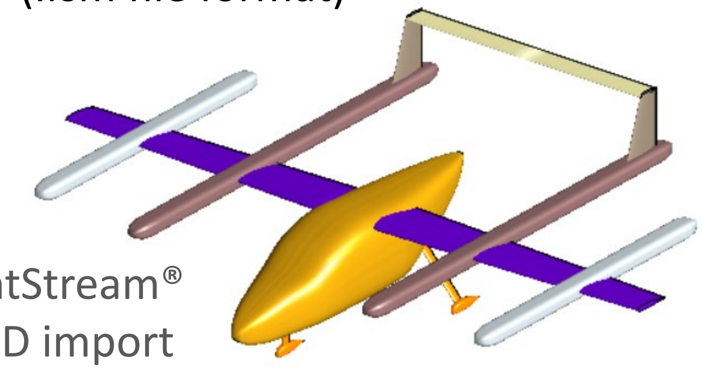
MATLAB-to-AC3D geometry export

AC3D geometry
(.ac file format)



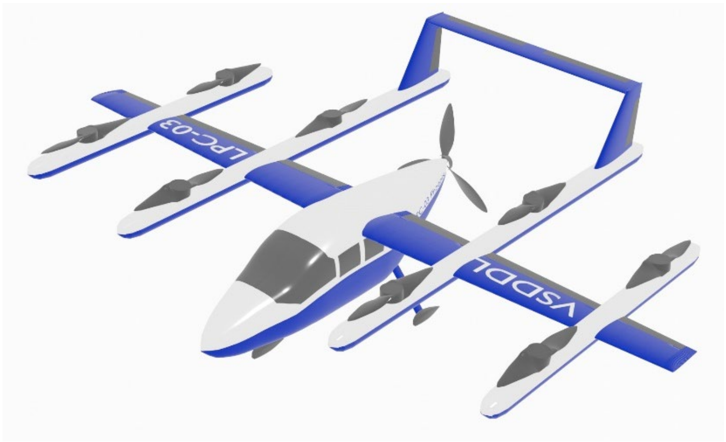
FlightStream® AC3D import

FlightStream® model
(.fsm file format)

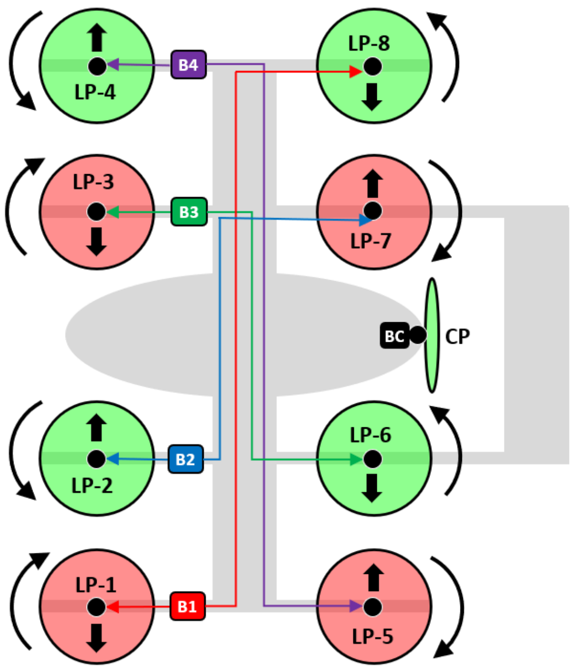


Blender

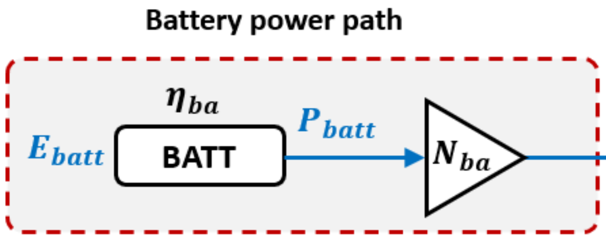
X-Plane model

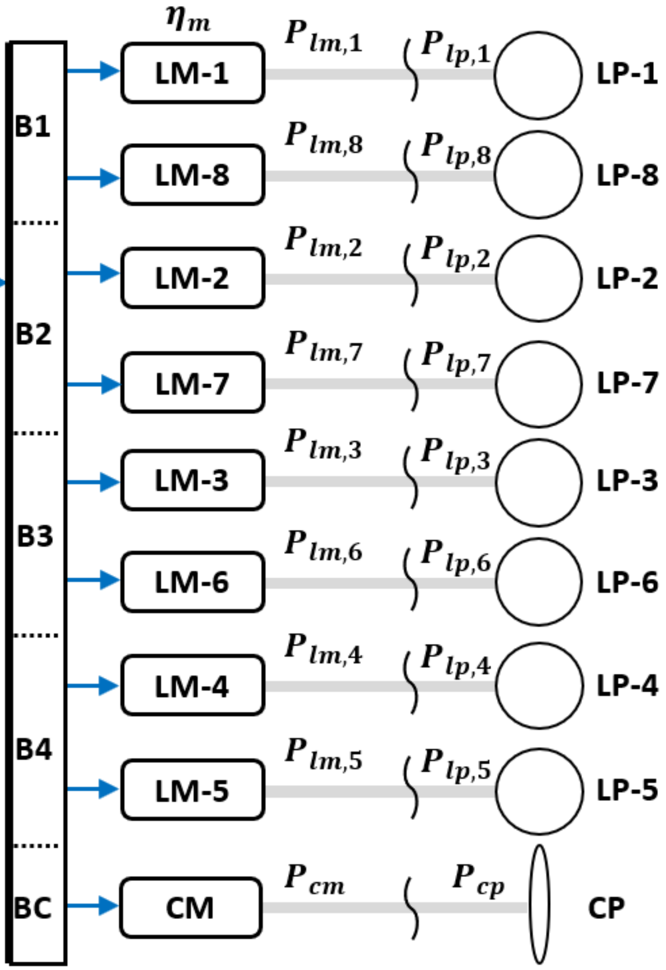


Power Flow Relationships: All-Electric (AE) Propulsion System Architecture



BATT: battery
P: propulsor
M: motor





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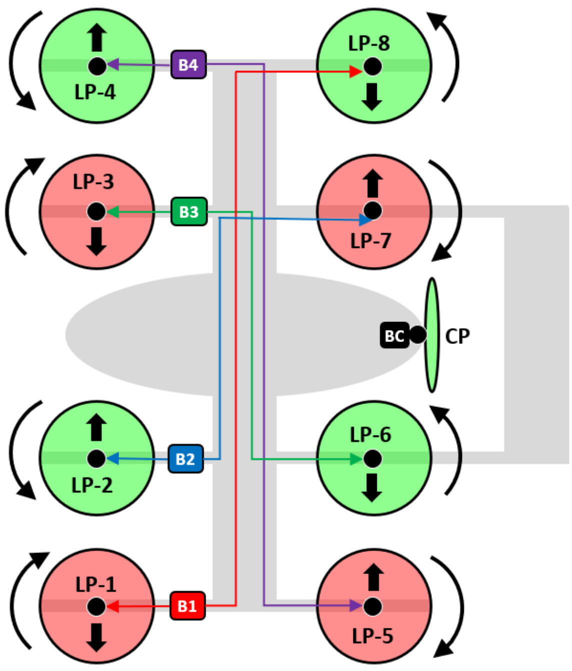
Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022)

Power Flow Relationships: Turbo-Electric (TE) Propulsion System Architecture



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0&0&0&0&0&1&0&0&0&0&0&0&0\\
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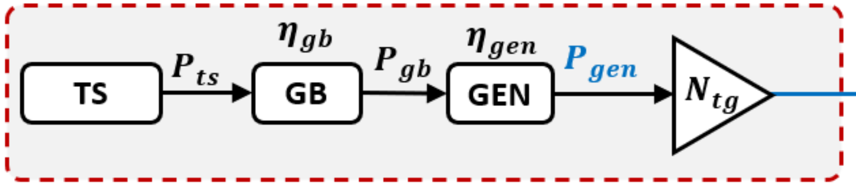
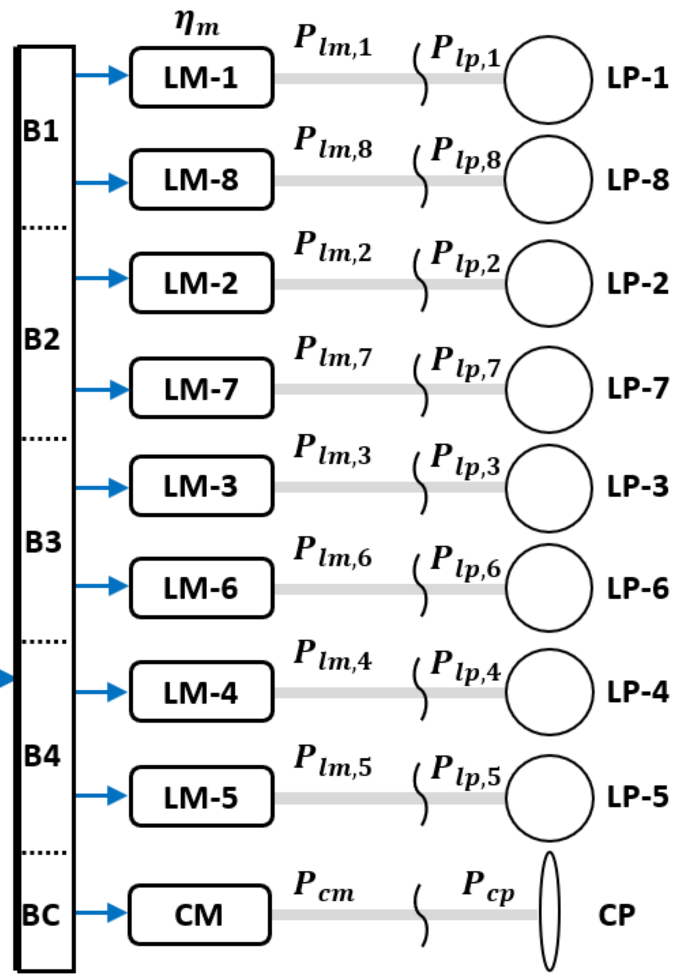
0&0&0&0&0&0&0&0&1&0&0&0&0\\
1&1&1&1&1&1&1&1&1&0&0&0&-\eta_m\\
0&0&0&0&0&0&0&0&0&\eta_{gb}&-1&0&0\\
0&0&0&0&0&0&0&0&0&0&\eta_{gen}&-1&0\\
0&0&0&0&0&0&0&0&0&0&0&N_{tg}&-1
\end{pmatrix}}_{A_{TE}}
\underbrace{\begin{bmatrix}P_{lm,1}\\P_{lm,2}\\P_{lm,3}\\P_{lm,4}\\P_{lm,5}\\P_{lm,6}\\P_{lm,7}\\P_{lm,8}\\P_{cm}\\P_{ts}\\P_{gb}\\P_{gen}\\P_2\end{bmatrix}}_{X_{TE}}
=
\underbrace{\begin{bmatrix}P_{lp,1}\\P_{lp,2}\\P_{lp,3}\\P_{lp,4}\\P_{lp,5}\\P_{lp,6}\\P_{lp,7}\\P_{lp,8}\\P_{cp}\\0\\0\\0\\0\end{bmatrix}}_{B_{TE}}
$$



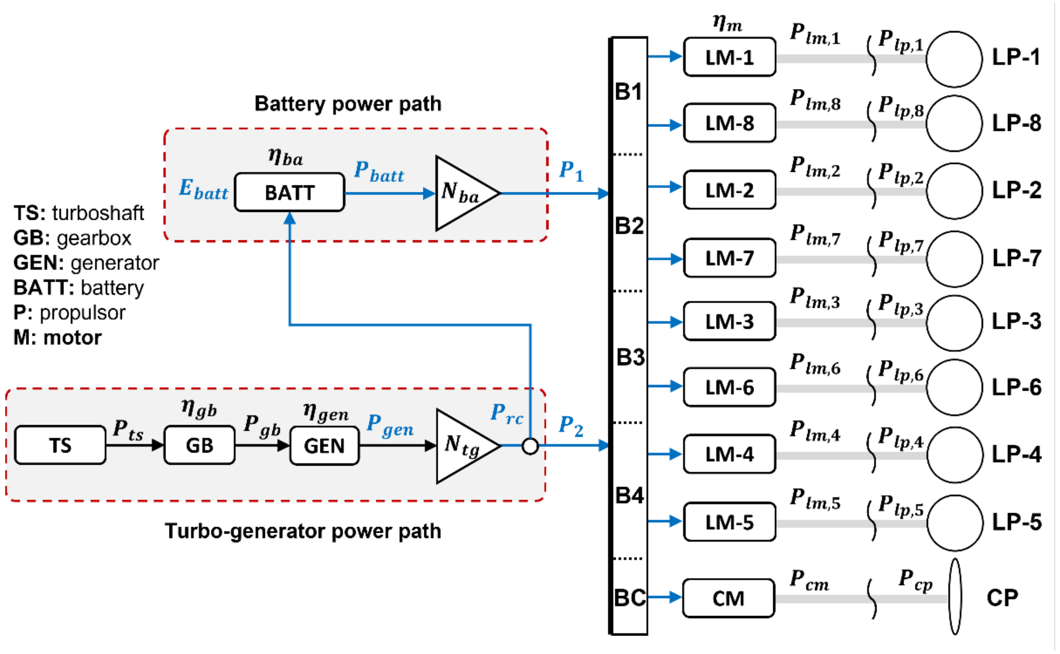
TS: turboshaft
GB: gearbox
GEN: generator
P: propulsor
M: motor

Turbo-generator power path



Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022)

Power Flow Relationships: Hybrid-Electric (HE) Propulsion System Architecture



- In this architecture, the **battery power path** and **turbo-generator power path** are **both** present; multiple ways of supplying the propulsor power needs
- The turbo-generator path can also **recharge** the battery/batteries

$$
\underbrace{\begin{pmatrix}
1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&0&0&0&0&0&\eta_{\mathrm{gb}}&-1&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&\eta_{\mathrm{gen}}&-1&0\\
0&0&0&0&0&0&0&0&0&0&0&0&-1&0&0&N_{\mathrm{tg}}&-1\\
0&0&0&0&0&0&0&0&0&0&0&\alpha_1&\beta_1&\gamma_1&0&0&\delta_1\\
0&0&0&0&0&0&0&0&0&0&0&\alpha_2&\beta_2&\gamma_2&0&0&\delta_2
\end{pmatrix}}_{A_{\mathrm{HE}}}
\underbrace{\begin{bmatrix}
P_{\mathrm{lm},1}\\P_{\mathrm{lm},2}\\P_{\mathrm{lm},3}\\P_{\mathrm{lm},4}\\P_{\mathrm{lm},5}\\P_{\mathrm{lm},6}\\P_{\mathrm{lm},7}\\P_{\mathrm{lm},8}\\P_{\mathrm{cm}}\\P_{\mathrm{batt}}\\\dot{E}_{\mathrm{batt}}\\P_1\\P_2\\P_{\mathrm{ts}}\\P_{\mathrm{gb}}\\P_{\mathrm{gen}}\\P_{\mathrm{rc}}
\end{bmatrix}}_{X_{\mathrm{HE}}}
=
\underbrace{\begin{bmatrix}
P_{\mathrm{lp},1}\\P_{\mathrm{lp},2}\\P_{\mathrm{lp},3}\\P_{\mathrm{lp},4}\\P_{\mathrm{lp},5}\\P_{\mathrm{lp},6}\\P_{\mathrm{lp},7}\\P_{\mathrm{lp},8}\\P_{\mathrm{cp}}\\0\\0\\0\\0\\0\\0\\b_1\\b_2
\end{bmatrix}}_{B_{\mathrm{HE}}}
$$

- The HE architecture **does not** have a **unique** solution
- To "square up" the system and solve it, **closure relationships** must be added to specify the **operating mode** of the propulsion system

Closure relationships ➡

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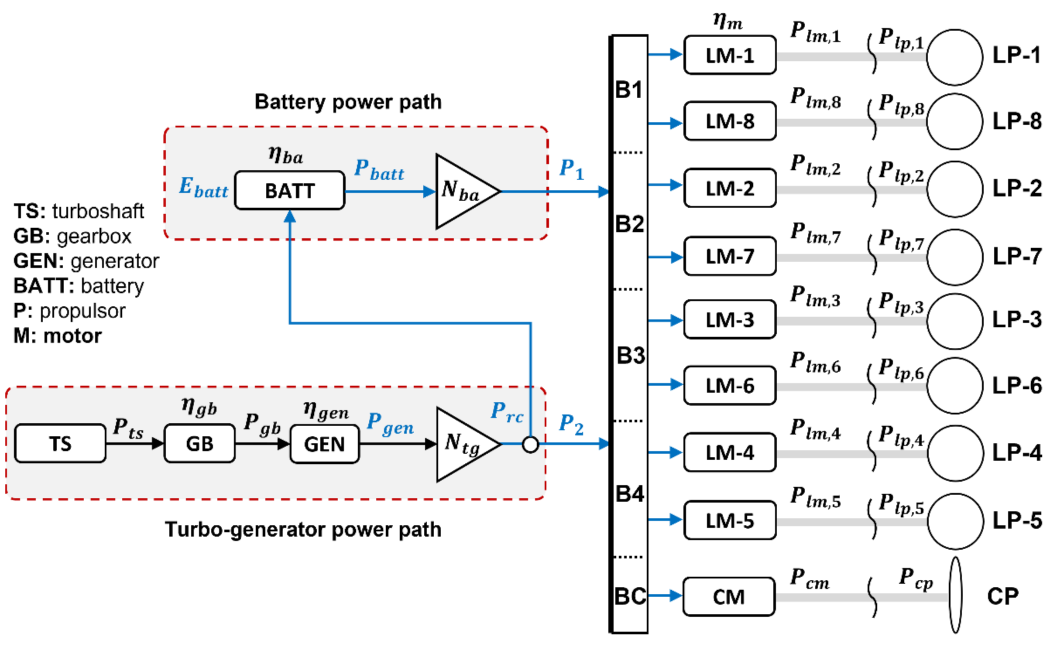
Hybrid-Electric (HE) Propulsion System Architecture – Operating Modes



$$
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1&1&1&1&1&1&1&1&1&0&0&-\eta_m&-\eta_m&0&0&0&0\\
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0&0&0&0&0&0&0&0&0&\frac{N_{\mathrm{ba}}}{\eta_{\mathrm{ba}}}&1&0&0&0&0&0&-\eta_{\mathrm{ba}}\\
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0&0&0&0&0&0&0&0&0&0&0&0&0&0&\eta_{\mathrm{gen}}&-1&0\\
0&0&0&0&0&0&0&0&0&0&0&0&-1&0&0&N_{\mathrm{tg}}&-1\\
0&0&0&0&0&0&0&0&0&0&0&\alpha_1&\beta_1&\gamma_1&0&0&\delta_1\\
0&0&0&0&0&0&0&0&0&0&0&\alpha_2&\beta_2&\gamma_2&0&0&\delta_2
\end{pmatrix}}_{A_{\mathrm{HE}}}
\underbrace{\begin{bmatrix}
P_{\mathrm{lm},1}\\ P_{\mathrm{lm},2}\\ P_{\mathrm{lm},3}\\ P_{\mathrm{lm},4}\\ P_{\mathrm{lm},5}\\ P_{\mathrm{lm},6}\\ P_{\mathrm{lm},7}\\ P_{\mathrm{lm},8}\\ P_{\mathrm{cm}}\\ P_{\mathrm{batt}}\\ \dot{E}_{\mathrm{batt}}\\ P_1\\ P_2\\ P_{\mathrm{ts}}\\ P_{\mathrm{gb}}\\ P_{\mathrm{gen}}\\ P_{\mathrm{rc}}
\end{bmatrix}}_{X_{\mathrm{HE}}}
=
\underbrace{\begin{bmatrix}
P_{\mathrm{lp},1}\\ P_{\mathrm{lp},2}\\ P_{\mathrm{lp},3}\\ P_{\mathrm{lp},4}\\ P_{\mathrm{lp},5}\\ P_{\mathrm{lp},6}\\ P_{\mathrm{lp},7}\\ P_{\mathrm{lp},8}\\ P_{\mathrm{cp}}\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ b_1\\ b_2
\end{bmatrix}}_{B_{\mathrm{HE}}}
$$

- **Nominal mode:** Used in FFM. Lift props inactive. Cruise prop power met using TG's.
  - Closure relationships:

1. No power in path P1: $\boldsymbol{\alpha_1 = 1, b_1 = 0}$
2. No recharging, $P_{rc} = 0$: $\boldsymbol{\delta_2 = 1, b_2 = 0}$

- **Recharge mode:** TG's supply cruise power and also recharge batteries at rate λ_{rc}.
  - Closure relationships:

1. No power in path P1: $\boldsymbol{\alpha_1 = 1, b_1 = 0}$
2. Recharge rate, $P_{rc} = \lambda_{rc}$: $\boldsymbol{\delta_2 = 1, b_2 = \lambda_{rc}}$

- **Offset mode:** Used in VFM. TG's operate at available power to offset load on batteries.
  - Closure relationships:

1. TG output $P_{ts} = P_{ts,av} \rightarrow \boldsymbol{\gamma_1 = 1, b_1 = P_{ts,av}}$
2. No recharging, $P_{rc} = 0$: $\boldsymbol{\delta_2 = 1, b_2 = 0}$

Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022)

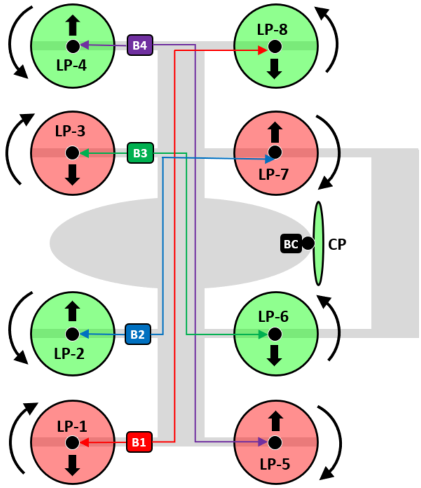
Power Sizing – Point Performance Constraints

- **"Power sizing": Determine the required rated power of propulsion system components that satisfy point performance constraints**

- **For AE:**
  A single battery pack failure was considered
  for Case 3 (cruise, degraded), Case 6 (climb, HH, degraded), Case 13/14 (hover OGE, sea-level, LP 1&8 or 2&7 INOP), and Case 21/22 (hover OGE, high-hot, LP 1&8 or 2&7 INOP)

- **For HE** (2 turbo-generators):
  FFM and sea-level hover
  met using TG's; for remaining cases, TG's + BATT;
  Case 7 (hover, SL) & 15 (hover, HH) assume 1 BATT or 1 TG failure; Cases 13, 14, 21, 22 (two lift props INOP at sea-level or high-hot) assume 1 BATT failure

- **For TE** (3 TG's):
  1 failed TG considered for
  Case 3 (cruise, degraded),
  Case 6 (climb, degraded),
  Case 7 (hover OGE, sea-level),
  Case 15 (hover OGE, high-hot)



Nominal & off-nominal point performance constraints for propulsions system sizing

Case #	Case Description	Flight Mode	Airspeed (knots)	Press. Alt (ft)	Density Alt (ft)	ΔISA (∘C)	R/C (fpm)	Payload %
1	Cruise, high	FFM	V_c KTAS	8,000	8,000	-	-	100%
2	Cruise, low	FFM	V_c KTAS	3,000	3,000	-	-	100%
3	Cruise, degraded	FFM	0.85 V_c KTAS	3,000	3,000	-	-	100%
4	Climb, SL	FFM	V_{th} + 10 KEAS	0	0	-	1,200	100%
5	Climb, HH	FFM	V_{th} + 10 KEAS	6,000	7,160	+10	1,000	100%
6	Climb, HH, degraded	FFM	V_{th} + 10 KEAS	6,000	7,160	+10	500	100%
7	HOGE, SL	VFM	-	0	0	-	-	100%
8	Vert. climb, SL	VFM	-	0	0	-	1,000	100%
9	HOGE, SL, LP-1 INOP	VFM	-	0	0	-	100	100%
10	HOGE, SL, LP-2 INOP	VFM	-	0	0	-	100	100%
11	HOGE, SL, LP-5 INOP	VFM	-	0	0	-	100	100%
12	HOGE, SL, LP-6 INOP	VFM	-	0	0	-	100	100%
13	HOGE, SL, LP-1,8 INOP	VFM	-	0	0	-	100	100%
14	HOGE, SL, LP-2,7 INOP	VFM	-	0	0	-	100	100%
15	HOGE, HH	VFM	-	6,000	7,160	+10	-	75%
16	Vert. climb, HH	VFM	-	6,000	7,160	+10	500	75%
17	HOGE, HH, LP-1 INOP	VFM	-	6,000	7,160	+10	100	75%
18	HOGE, HH, LP-2 INOP	VFM	-	6,000	7,160	+10	100	75%
19	HOGE, HH, LP-5 INOP	VFM	-	6,000	7,160	+10	100	75%
20	HOGE, HH, LP-6 INOP	VFM	-	6,000	7,160	+10	100	75%
21	HOGE, HH, LP-1,8 INOP	VFM	-	6,000	7,160	+10	100	75%
22	HOGE, HH, LP-2,7 INOP	VFM	-	6,000	7,160	+10	100	75%

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Power Sizing – Finding Sizing Power Requirements of Propulsion System Components

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Key takeaways:

- Failure/off-nominal scenarios must be considered! These size some components.
- The explicit analysis of *trim* allows these to be captured! No trim, no flight!

Lift prop motor is sized by one of the 1-prop inoperative scenarios

The cruise motor gets sized by the climb requirement

Battery pack peak output power is sized by the battery pack failure scenario

Case #	Case Description	Flight Mode	Airspeed (knots)	Press. Alt (ft)	Density Alt (ft)	ΔISA (∘C)	R/C (fpm)	Payload %
1	Cruise, high	FFM	V_c KTAS	8,000	8,000	-	-	100%
2	Cruise, low	FFM	V_c KTAS	3,000	3,000	-	-	100%
3	Cruise, degraded	FFM	0.85 V_c KTAS	3,000	3,000	-	-	100%
4	Climb, SL	FFM	V_{th} + 10 KEAS	0	0	-	1,200	100%
5	Climb, HH	FFM	V_{th} + 10 KEAS	6,000	7,160	+10	1,000	100%
6	Climb, HH, degraded	FFM	V_{th} + 10 KEAS	6,000	7,160	+10	500	100%
7	HOGE, SL	VFM	-	0	0	-	-	100%
8	Vert. climb, SL	VFM	-	0	0	-	1,000	100%
9	HOGE, SL, LP-1 INOP	VFM	-	0	0	-	100	100%
10	HOGE, SL, LP-2 INOP	VFM	-	0	0	-	100	100%
11	HOGE, SL, LP-5 INOP	VFM	-	0	0	-	100	100%
12	HOGE, SL, LP-6 INOP	VFM	-	0	0	-	100	100%
13	HOGE, SL, LP-1,8 INOP	VFM	-	0	0	-	100	100%
14	HOGE, SL, LP-2,7 INOP	VFM	-	0	0	-	100	100%
15	HOGE, HH	VFM	-	6,000	7,160	+10	-	75%
16	Vert. climb, HH	VFM	-	6,000	7,160	+10	500	75%
17	HOGE, HH, LP-1 INOP	VFM	-	6,000	7,160	+10	100	75%
18	HOGE, HH, LP-2 INOP	VFM	-	6,000	7,160	+10	100	75%
19	HOGE, HH, LP-5 INOP	VFM	-	6,000	7,160	+10	100	75%
20	HOGE, HH, LP-6 INOP	VFM	-	6,000	7,160	+10	100	75%
21	HOGE, HH, LP-1,8 INOP	VFM	-	6,000	7,160	+10	100	75%
22	HOGE, HH, LP-2,7 INOP	VFM	-	6,000	7,160	+10	100	75%

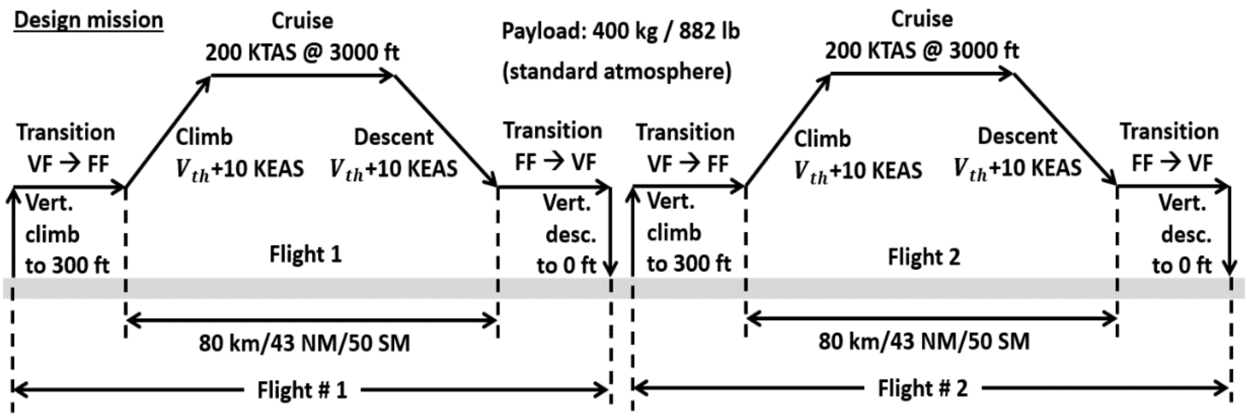
Pm1kW	Pm2kW	Pm3kW	Pm4kW	Pm5kW	Pm6kW	Pm7kW	Pm8kW	PcpkW	P1kW	PbattkW	EdotkW
0	0	0	0	0	0	0	0	211.21	222.32	44.464	-230.31
0	0	0	0	0	0	0	0	237.47	249.97	49.994	-258.95
0	0	0	0	0	0	0	0	161.94	170.46	42.615	-176.59
0	0	0	0	0	0	0	0	257.83	271.39	54.279	-281.15
0	0	0	0	0	0	0	0	250.75	263.95	52.789	-273.43
0	0	0	0	0	0	0	0	194.84	205.1	51.274	-212.47
59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	4.6735e-15	498.52	99.705	-516.44
67.632	66.436	66.436	67.632	69.392	70.63	70.63	69.392	0	577.03	115.41	-597.77
0	112.45	108.97	55.334	113.26	58.041	55.832	39.466	0	571.95	114.39	-592.51
106.52	0	70.987	105.79	70.306	104.88	35.345	69.758	0	593.25	118.65	-614.58
114.84	58.501	55.163	38.743	0	113.93	108.65	54.614	0	573.1	114.62	-593.7
69.774	101.96	27.863	70.306	104.85	0	72.527	105.56	0	581.94	116.39	-602.86
0	90.825	91.996	93.287	90.736	92.014	93.197	0	0	581.11	145.28	-602
93.284	0	90.81	92.014	91.995	93.212	0	90.739	0	581.11	145.28	-602
63.465	63.465	63.465	63.465	63.465	63.465	63.465	63.465	4.9672e-10	534.44	106.89	-553.65
67.649	67.294	67.294	67.649	68.135	68.46	68.46	68.135	0	571.66	114.33	-592.21
0	125.53	117.79	54.683	123.47	58.4	53.346	37.124	0	600.35	120.07	-621.93
116.56	0	75.266	112.75	73.288	110.49	17.758	70.12	0	606.57	121.31	-628.37
125.35	59.061	52.581	36.335	0	127.1	117.48	53.898	0	601.91	120.38	-623.55
72.091	108.47	18.497	71.046	114.63	0	76.406	113.38	0	604.76	12[illegible].95	-626.5
0	97.767	99.333	101.03	97.652	99.33	100.91	0	0	627.4	156.85	-649.95
101.05	0	97.729	99.364	99.299	100.95	0	97.639	0	627.4	156.85	-649.95

Power sizing constraints supplied to PEACE

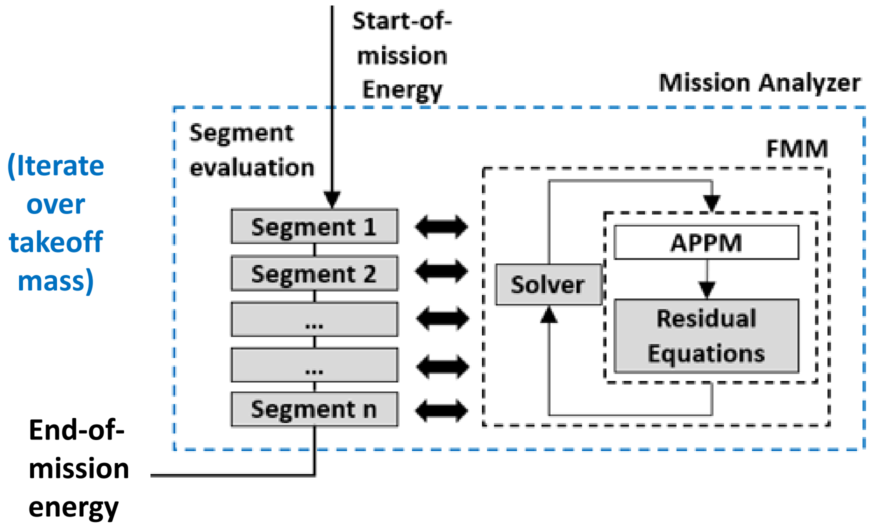
Example of AE architecture power flow model solution for a given iteration

Energy Sizing: Mission Performance Analysis

- **"Energy sizing": Determine the necessary capacities of energy sources (batteries and/or fuel) that satisfy the mission energy requirements and also reserve energy requirements**
- Two identical back-to-back missions ("out and back") missions were considered for the LPC UAM aircraft
- No distance credit for transitions between vertical and forward flight or vice versa
- End of (second) mission energy constraints:
  - 20% battery state-of-charge (SOC), i.e. no more than 80% depth-of-discharge
  - Reserve fuel 5% of trip fuel
- The Mission Analyzer will calculate the energy requirement segment-by-segment and compute the end-of-mission energy
  - The PEACE sizer will iterate over max takeoff mass (MTOM) until the end energy satisfies the energy reserve constraints



Notes:
1. No distance credit for transitions between vertical flight (VF) and forward flight (FF) modes
2. Battery state at conclusion of Flight # 2: 20% SOC (80% DOD)
3. Fuel state at conclusion of Flight #2: 5% of trip fuel



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Weight Estimation

- Weight estimation relationships (WERs) for GA aircraft were used to estimate structural and systems masses
- Propulsion system component masses were estimated based on power densities or metrics representing state-of-the-art
- Battery mass estimation accounted for both energy and peak power requirements

Energy required — Peak power

Battery Mass

$$m_{batt} = \max\left(\frac{E_{req}}{(E/M)_{batt}}, \frac{P_{peak}}{(P/M)_{batt}}\right)$$

Specific energy — Specific power

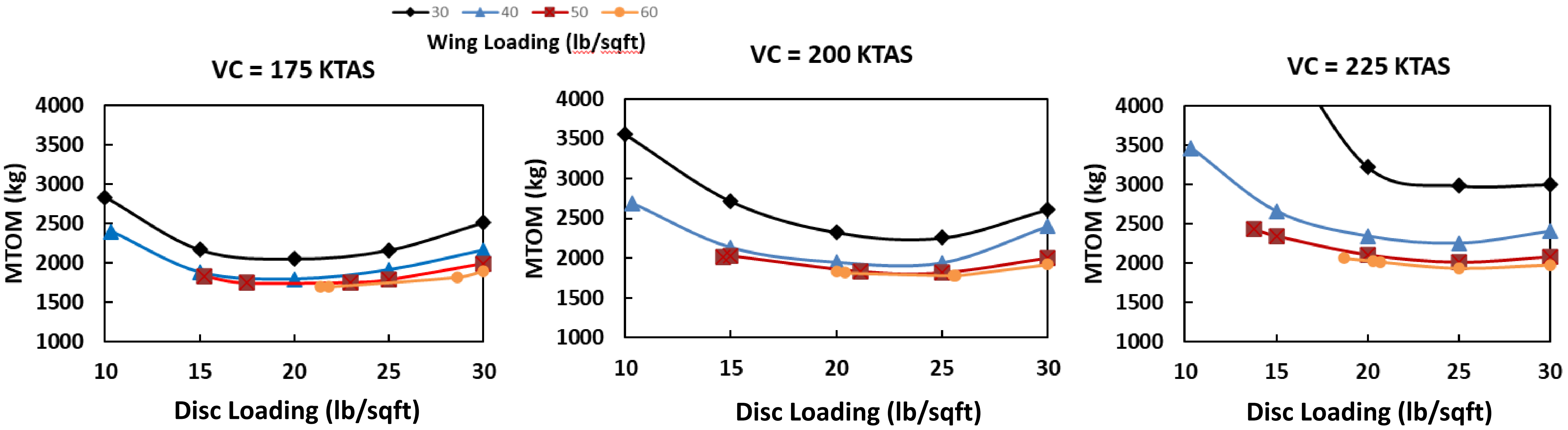
- Turboshaft engine mass, sfc, and dimension relationships were developed based on data for existing engines
- Based on component masses and locations (from geometry model), their impacts on aircraft CG and inertia tensor are computed

Component	Property	Value
Electric motors	Power-to-mass ratio	5 kW/kg
	Efficiency	95%
	Specific diameter	1.8 m/MW
	Specific length	1.3 m/MW
Gearbox	Power-to-mass ratio	24 kW/kg
	Efficiency	0.99
Generators	Power-to-mass ratio	6.25 kW/kg
	Efficiency	0.97
	Specific diameter	0.36 m/MW
	Specific length	0.61 m/MW
Cabling	Specific power	200 kVA · m/kg
	Efficiency	0.985
Batteries	Specific energy	(Varied)
	Efficiency	96%
	Maximum C-rate	(Varied)
	Specific power	(Computed)
Fuel	Specific energy	43 MJ/kg

For sources of technology SOTA parameters, see:

Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044 (also AIAA-2022-3513 @ AIAA AVIATION 2022)

Wing loading / Disc loading / Cruise Speed Sweeps



$$Wing\ loading = \frac{Vehicle\ weight}{Wing\ area}$$

In general, and within limits:

- Higher wing loading → more efficient cruise, but also higher takeoff/landing speeds, stall speeds

$$Disc\ loading = \frac{Vehicle\ weight}{rotor\ disc\ area}$$

In general, and within limits:

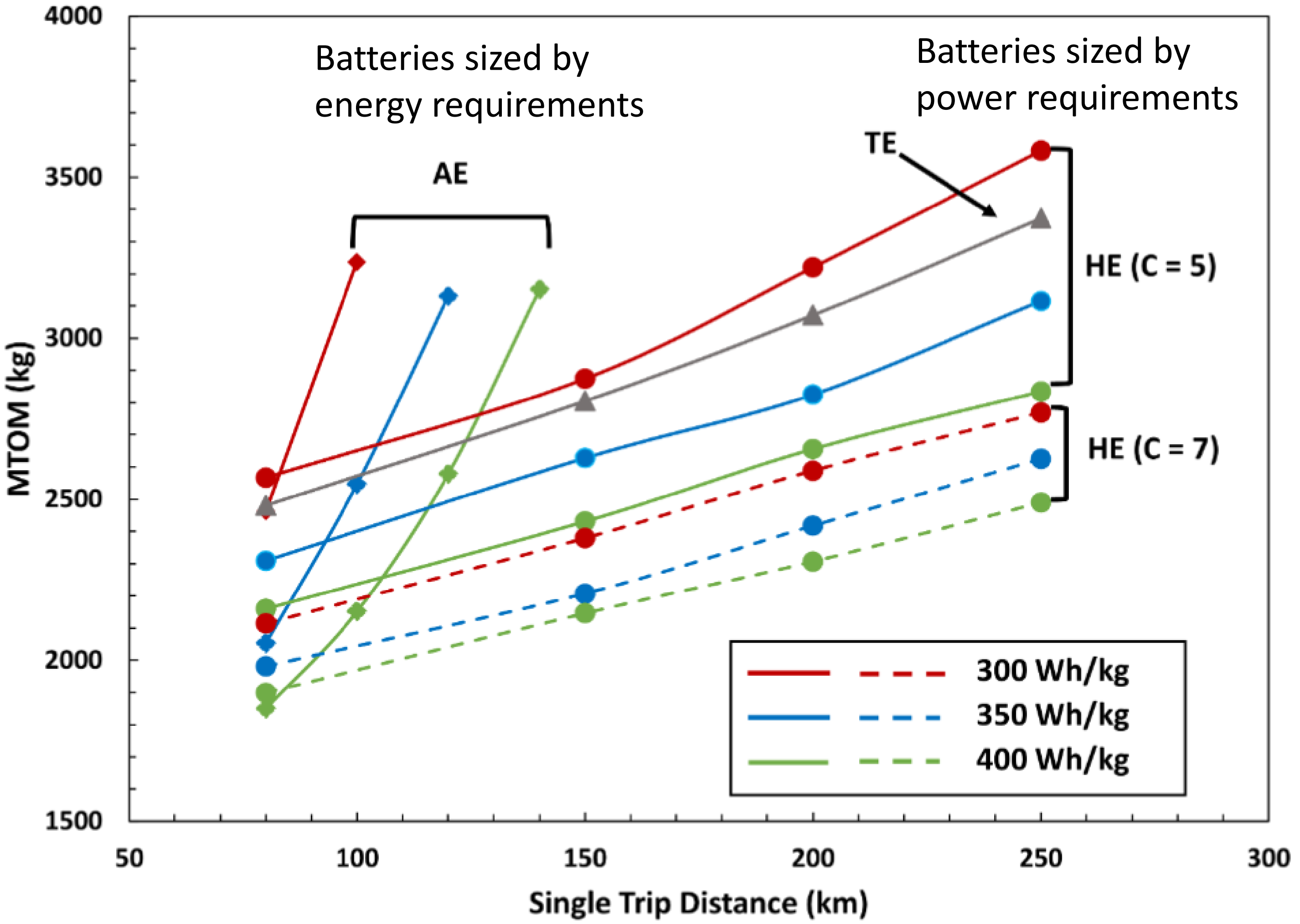
- Lower disc loading → higher hover efficiency, but bigger drag & weight penalties in forward flight

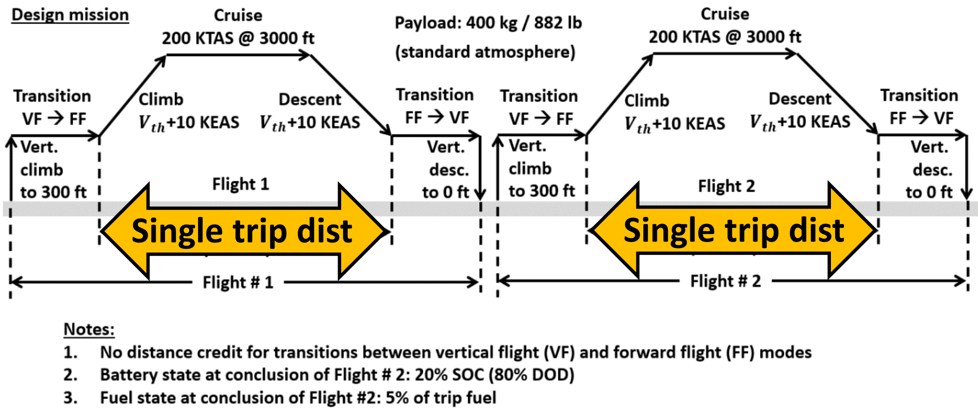
(1) In general, there is an increase in propulsive energy requirements with higher speeds, resulting in an increase in Maximum Takeoff Mass (MTOM)

(2) There is significant MTOM reduction when increasing from 30 to 40 psf wing loading; beyond 50 psf, diminishing returns are obtained

(3) Disc loading shows a bucket with an MTOM minimum around 20 psf, and increasing MTOM for both higher and lower disc loadings

Effect of Battery Specific Energy & C-Rate on AE, HE, and TE Sizing





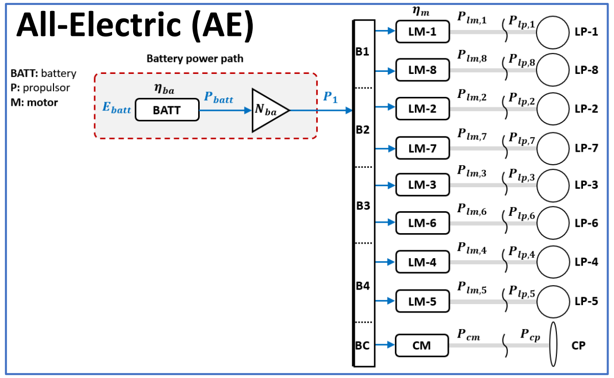
C-rate: Inverse of the time in hours required to discharge the battery at a steady rate

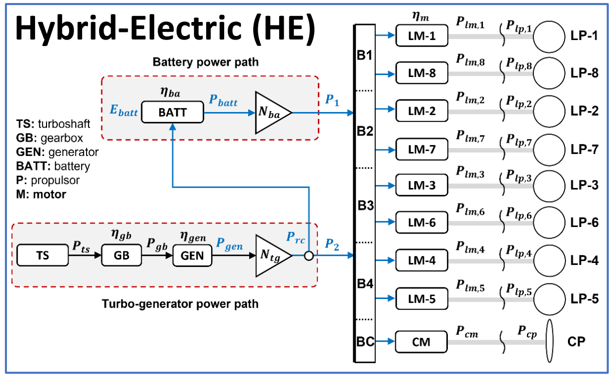
Relationship between **specific energy [Wh/kg]**, **specific power [W/kg]**, and **C-rate [1/h]:**

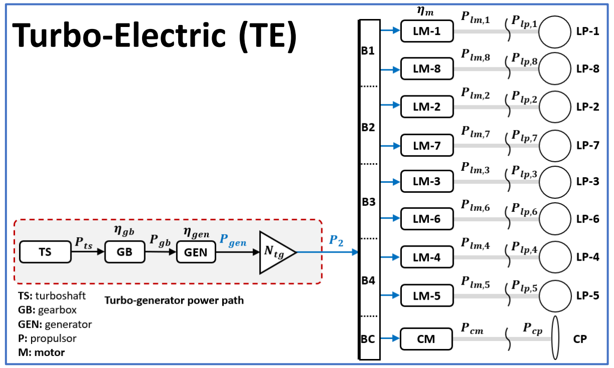
Spec. power [W/kg] = Spec. energy [Wh/kg] X C-rate [1/h]

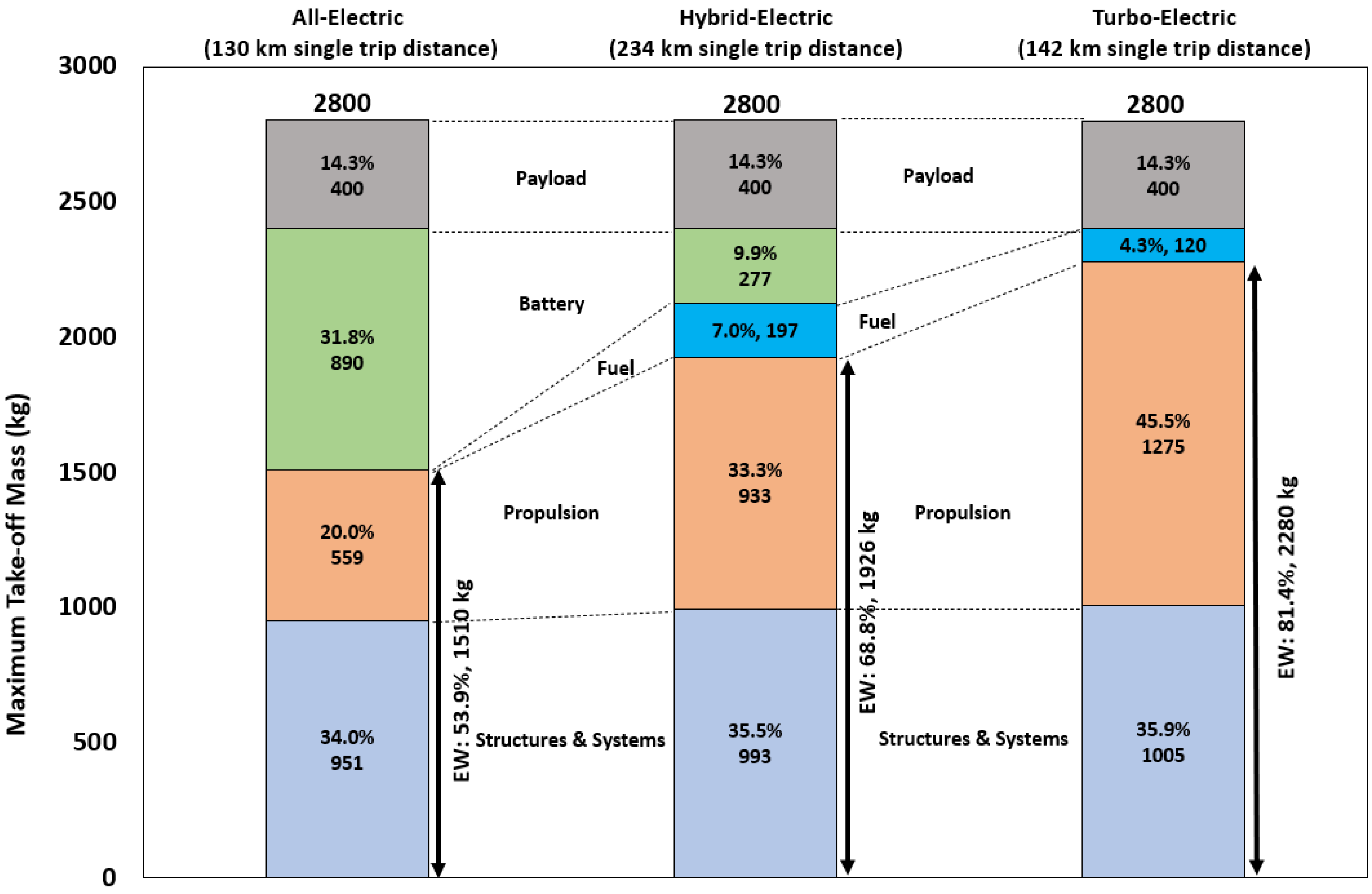
Chakraborty, I. and Mishra, A.A., "Sizing and Analysis of a Lift-Plus-Cruise Aircraft with Electrified Propulsion," AIAA Journal of Aircraft, Article in Advance, Nov 1, 2022, DOI: 10.2514/1.C037044

Weight Breakdown of AE, HE, and TE sized to same MTOM









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Optimization Problem Setup

Design variables

#	Design Variables	Type	Lower Bound	Upper Bound
1	Wing Loading	Continuous	30 lb/ft^2	80 lb/ft^2
2	Disc Loading	Continuous	10 lb/ft^2	30 lb/ft^2
3	Wing Aspect Ratio	Continuous	6	12
4	Wing Taper Ratio	Continuous	0.85	1
5	Cruise Velocity	Continuous	175 knots	225 knots
6	Propulsion Architecture	Discrete	1 (AE), 2 (HE), 3 (TE)	
7	Number of Battery Packs	Discrete	2	6

Optimization Algorithm

- Non-dominated Sorting Genetic Algorithm II (NSGA-II) sorts the individuals based on the non-domination level
- An individual dominates another if it is no worse than the other for all objectives, and strictly better in at least one objective
- For individuals with same non-dominance value, an individual with least crowding distance is selected

Objective functions

#	Objective Function	Unit
1	Maximum Takeoff Mass (MTOM)	kg
2	Energy used per unit distance per unit payload (E/(P-d))	kJ/(kg-km)
3	Energy Mass Fraction (total energy mass / MTOM)	-
4	Mission Time (single-trip)	min

In the optimization cases considered, **one, two, or three** of the above were applied

Link to recent paper on GA optimization:

Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

Optimization Cases

- Eight optimization cases were considered (described below). These varied in:
  - Objective functions that were used
  - Single-trip distance (80, 120, or 150 km)
  - Battery specific energy (350 or 400 Wh/kg)

- **Cases 1 and 2** were used to study the general impact of each design variable and the effect of including different objective functions. Thereafter, **Cases 3-8** were used to study the impact of single-trip distance and battery specific energy on the optimized generations

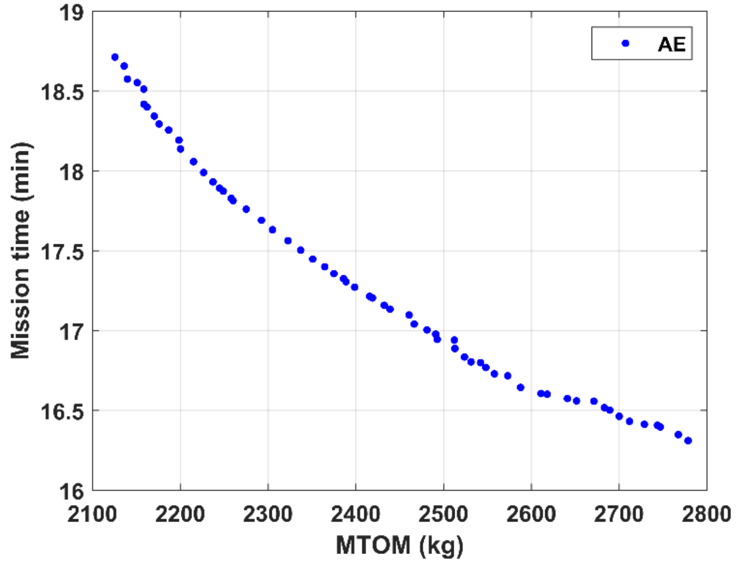
Case Number	Objective Functions	Single trip distance (km)	Battery Specific Energy (Wh/kg)
1	MTOM and Mission Time	80	400
2	MTOM, Energy Mass Fraction, E/(P-d)	80	400
3	MTOM, E/(P-d)	80	400
4	MTOM, E/(P-d)	80	350
5	MTOM, E/(P-d)	120	400
6	MTOM, E/(P-d)	120	350
7	MTOM, E/(P-d)	150	400
8	MTOM, E/(P-d)	150	350

Will focus on these cases.

The rest are in the paper

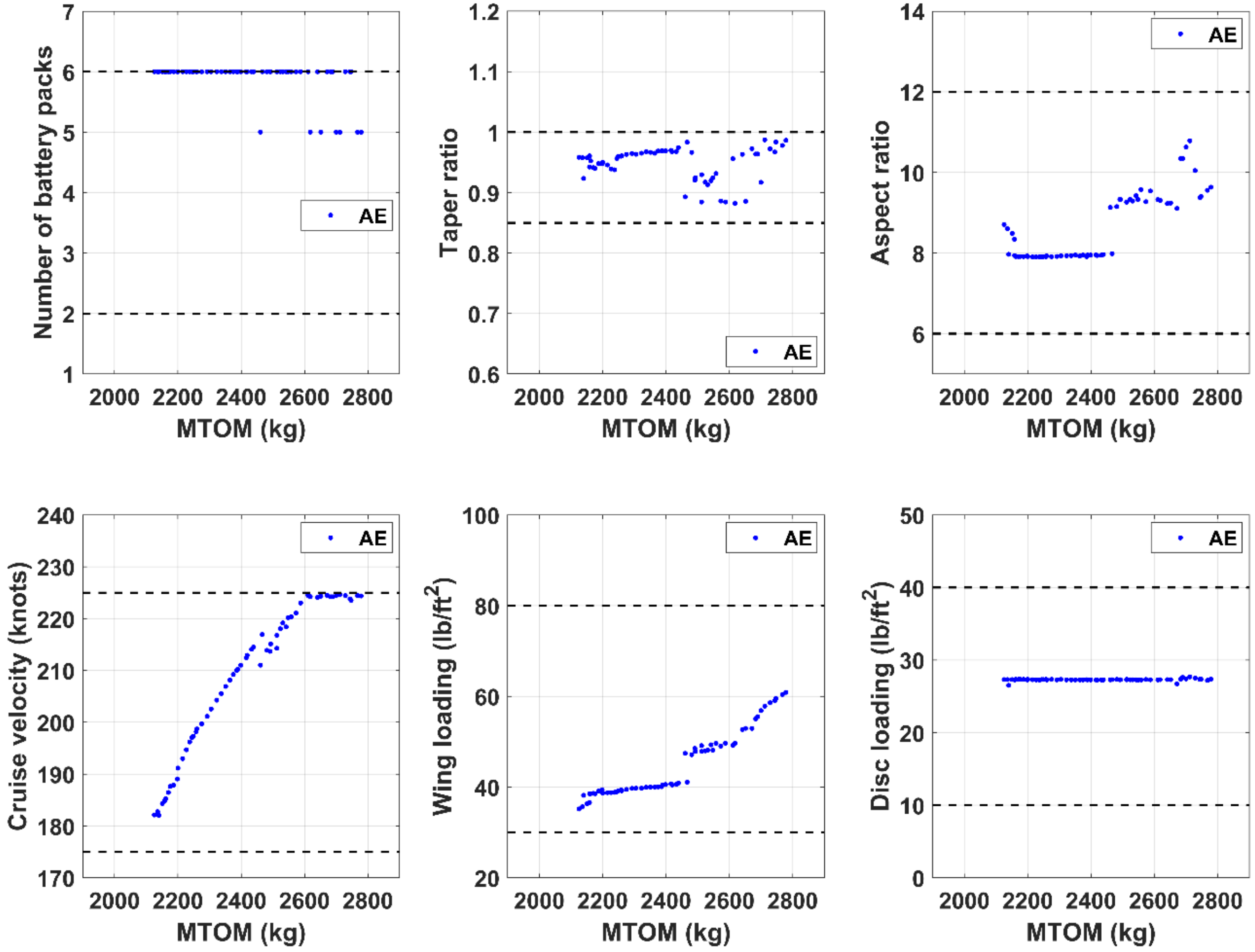
Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

Case 1: Objective Functions MTOM and Mission Time



MTOM vs Mission Time

- For this short distance (80 km), only the AE architecture appears in the final generation
- Significant penalty associated with cruising faster: 600 kg MTOM increase for 3 minutes time savings
- DL is constant around 28 lb/ft^2
- WL increases with cruise speed to maintain cruise lift coefficient at an efficient value



MTOM vs Design variables

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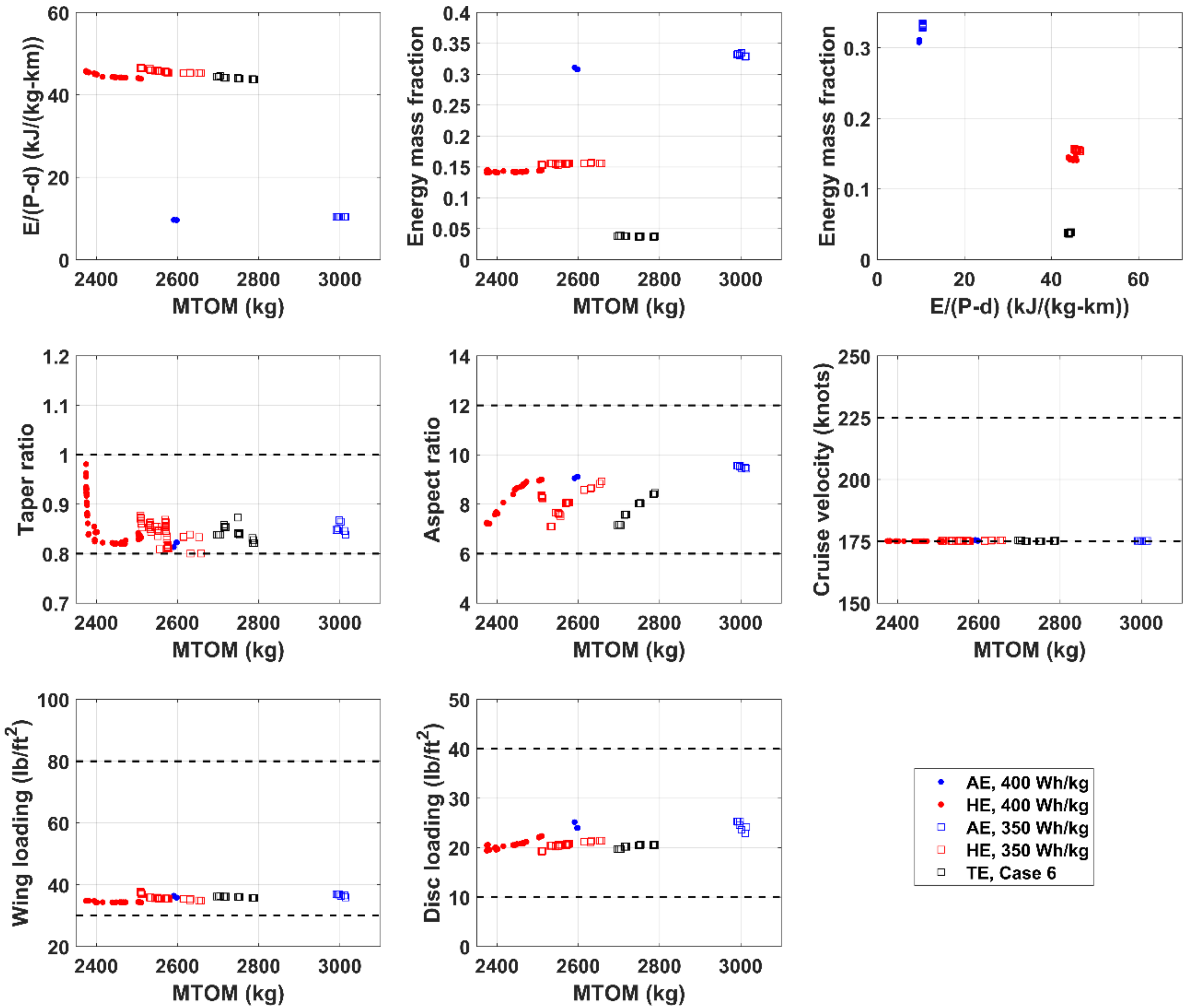
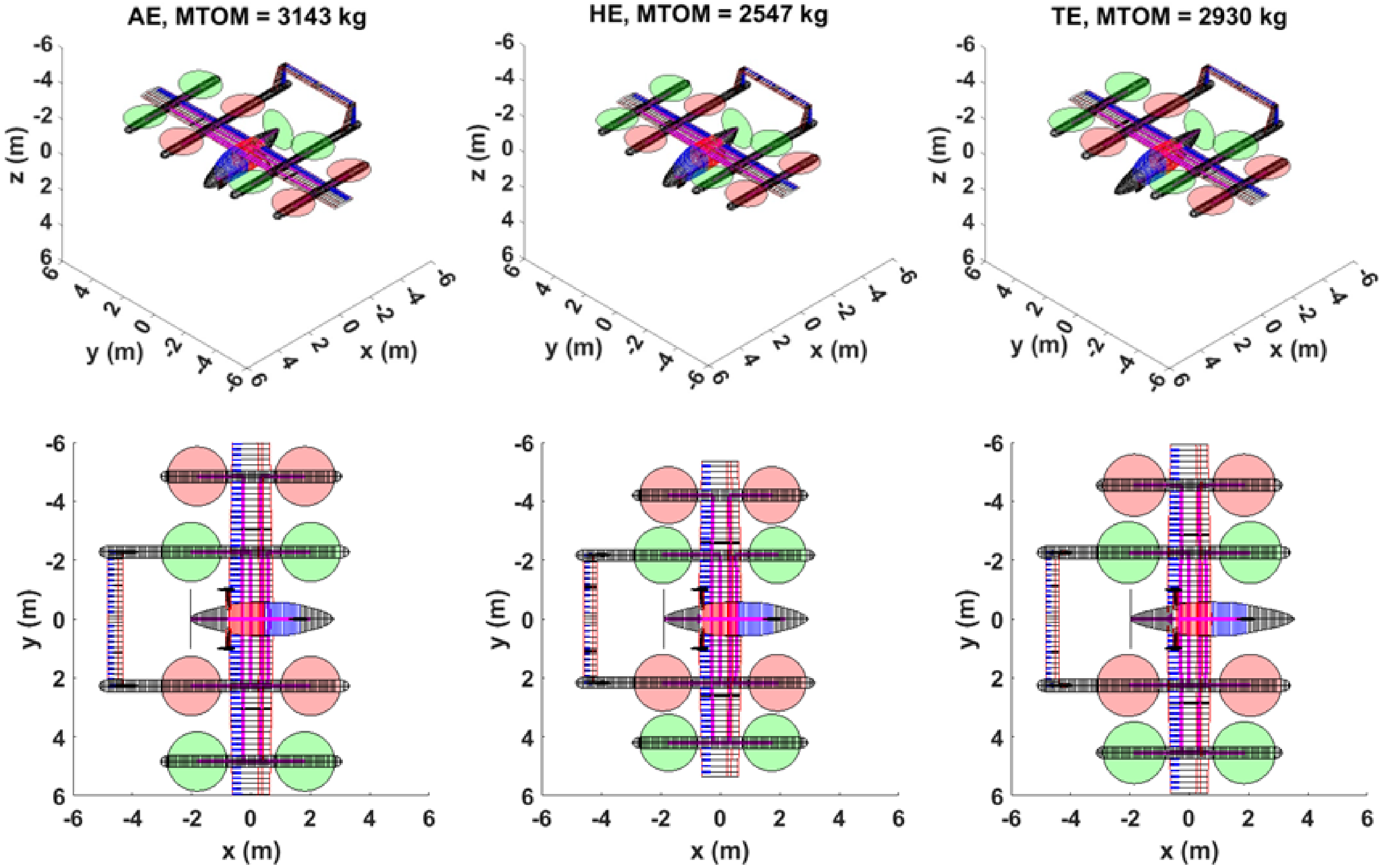
Bhandari, R., Mishra, A.A., and Chakraborty, I., **"Genetic Algorithm Optimization of Lift-Plus-Cruise VTOL Aircraft with Electrified Propulsion,"** AIAA SCITECH 2023, National Harbor, MD, Jan 23-27, 2023, AIAA-2023-0398

Case 5 (120 km, 400 Wh/kg) & Case 6 (120 km, 350 Wh/kg)

- At 350 Wh/kg battery specific energy, AE, HE, and TE designs show up in the final generation
  - At 400 Wh/kg, only AE and HE designs
- When sized for these trip distances, AE designs are considerably heavier than HE and TE designs
- With cruise velocity no longer an objective function, optimized designs tend to cruise at the lower bound of 175 KTAS
- E/(P-d) for HE and TE are similar (as jet fuel is expended for cruise), but it is lower for AE
- Increasing AR was generally associated with an increase in MTOM and slight reduction in E/(P-d)
- Similar observations, but more pronounced, when trip distance is increased to 150 km (specific energy 350 Wh/kg & 400 Wh/kg)



Comparison of Sized Geometries



Design Variables	Design Variables	Design Variables
DL : 26.7 lb/ft^2	DL : 22.1 lb/ft^2	DL: 21.4 lb/ft^2
WL: 37.1 lb/ft^2	WL: 36.6 lb/ft^2	WL: 37 lb/ft^2
V : 175 KTAS	V : 175 KTAS	V : 175 KTAS
TR : 0.82	TR : 0.85	TR : 0.84
AR : 9.18	AR : 8.03	AR : 8.63

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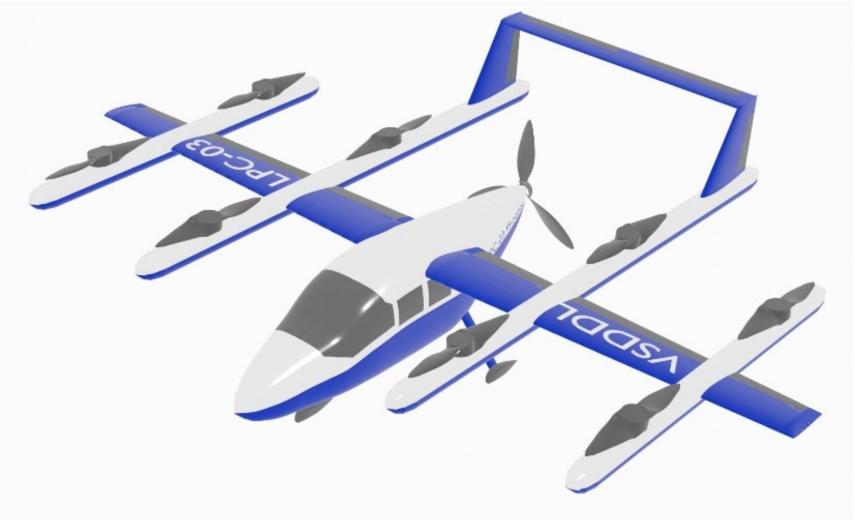
Conclusions and Observations

- The Parametric Energy-based Aircraft Configuration Evaluator (PEACE) framework enables the sizing and performance analysis of a wide range of flight vehicles with novel configurations and propulsion system architectures

- Some salient features of PEACE w.r.t. analysis of VTOL aircraft
  - Explicit consideration of control allocation and trim
  - Explicit consideration of post-failure/off-nominal scenarios for power sizing
  - Trim and post-failure scenarios can directly size some power system components
  - The sized vehicle definition from PEACE feeds directly into MADCASP
    - Control law development (topic of Webcast 2, March 1)
    - Piloted simulation studies (topic of Webcast 3, March 8)

- Modular implementation allows analysis modules to be upgraded/added as required. For example:
  - Physics-based lifting surface weight estimation (WIP)
  - More detailed propulsion system component models (WIP)



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