U.S. AIR FORCE

USSF

AFRL

Gradient-Based Optimization of Power and Thermal Management Systems

Tool Design and Application to MDO Problems

Christopher T. Aksland, University of Illinois

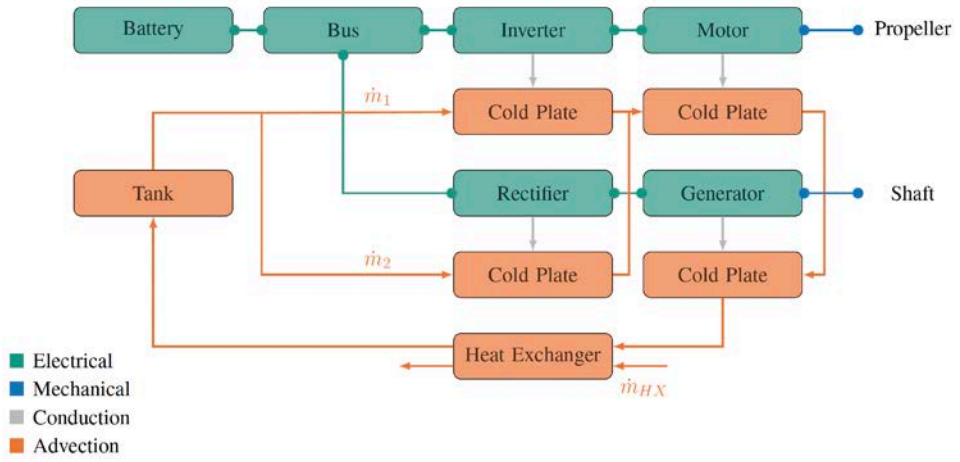
Christopher A. Lupp, AFRL/RQVC

Daniel L. Clark, Jr., AFRL/RQVC

Andrew G. Alleyne, University of Minnesota

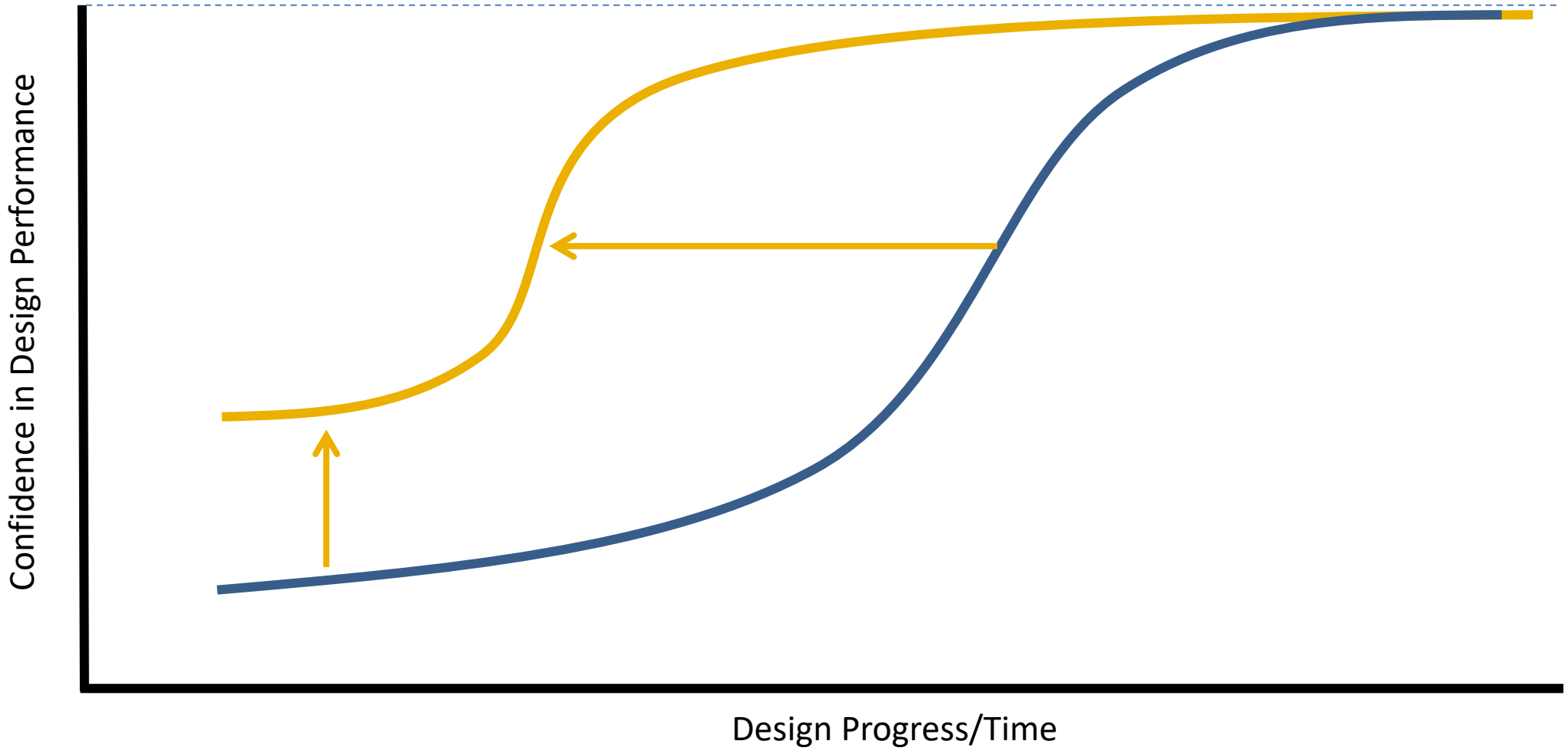
Gradient-Based PTMS Optimization

- Motivation
- Tool Development
  - Existing tools
  - Initial tool design
  - Revised approach
- Studies
  - Vehicle/sub-system co-design
  - Feedback controller sizing
  - Coupled vehicle/sub-system/controller sizing
- Concluding Remarks
  - Lessons learned
  - Contributions

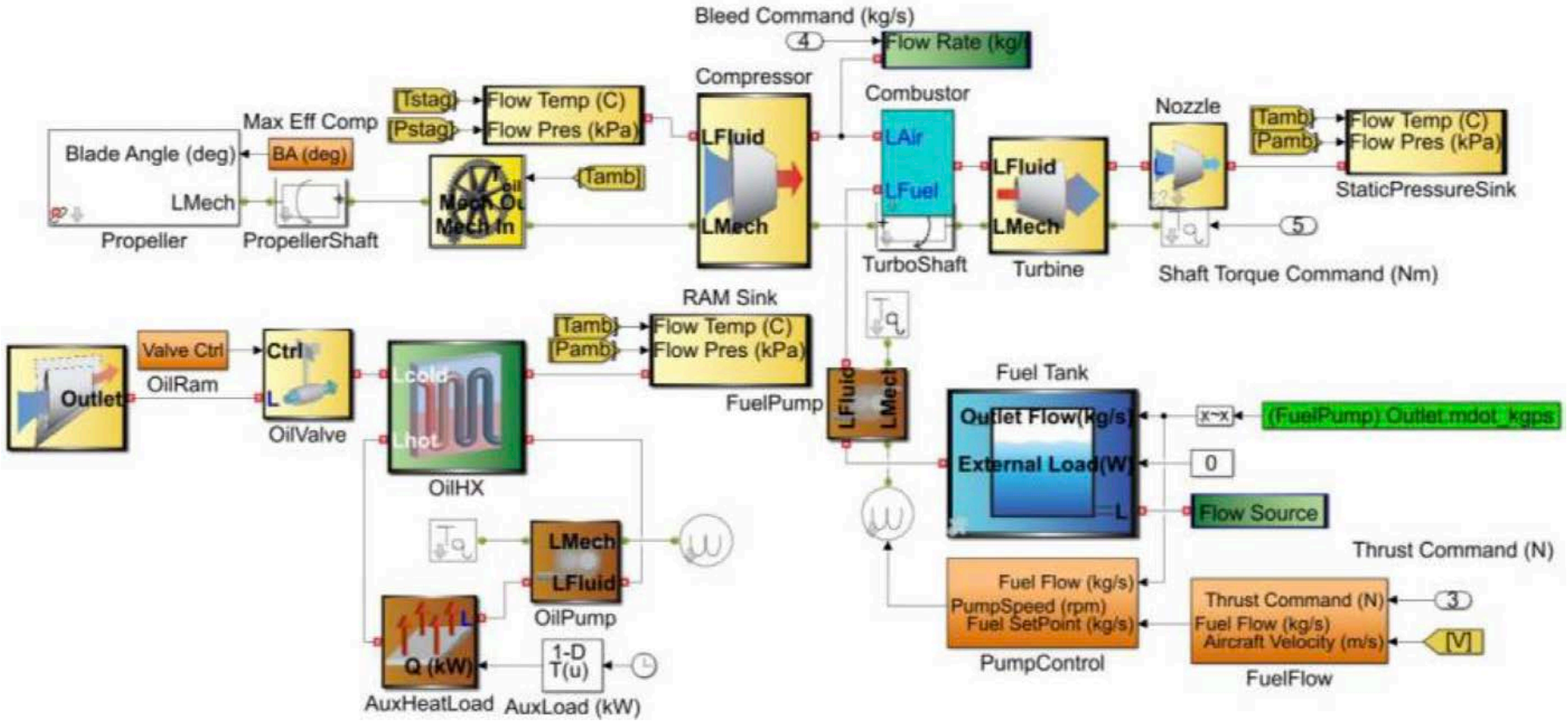


Motivation

We seek to increase confidence in performance during design.



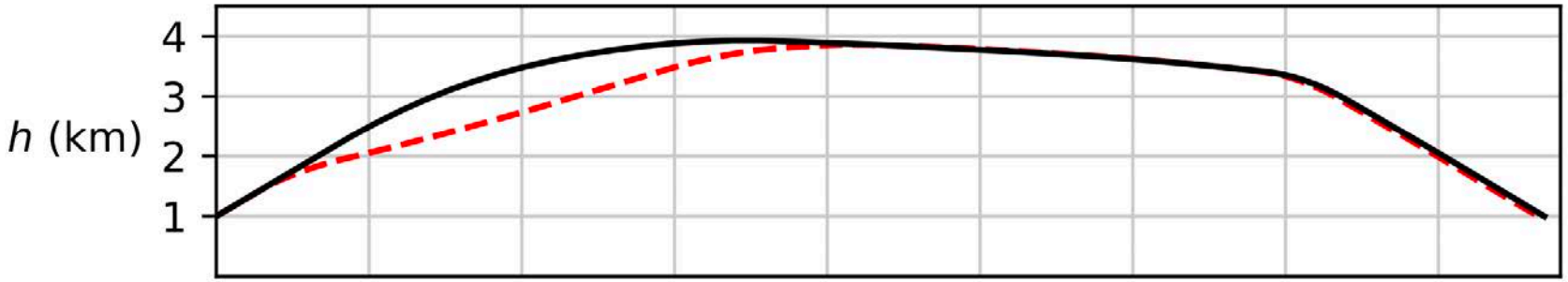
PTMS modeling includes high complexity subsystems.

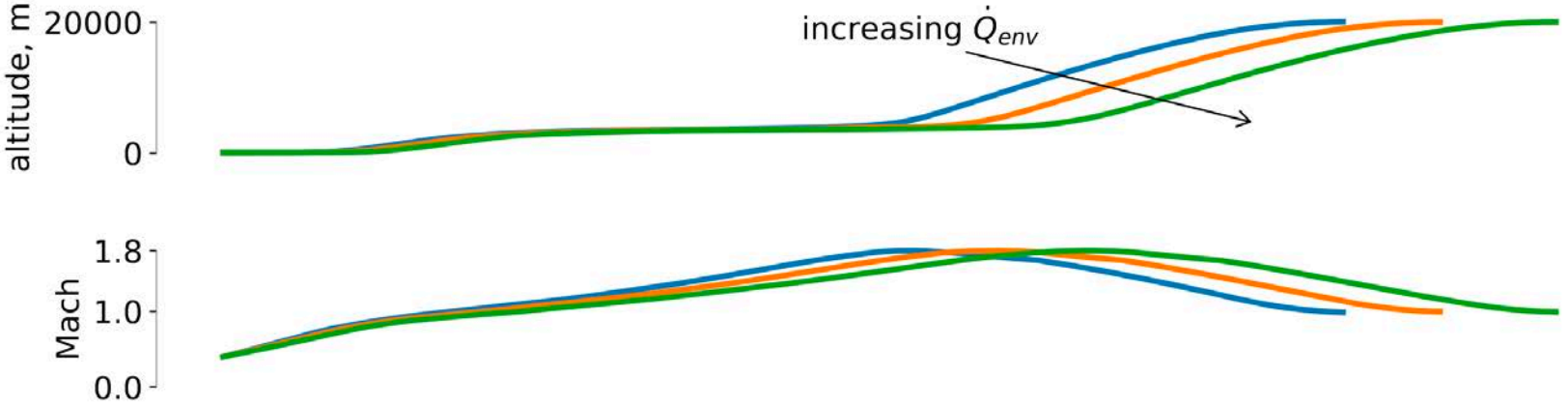


Turboprop model (Abolmoali et al., 2020)

PTMS optimization highlights thermally limited vehicles.

Falck, et al., 2017

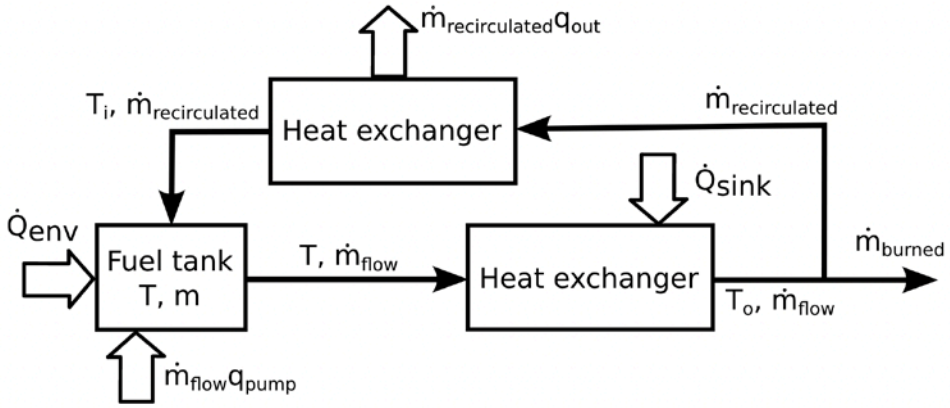




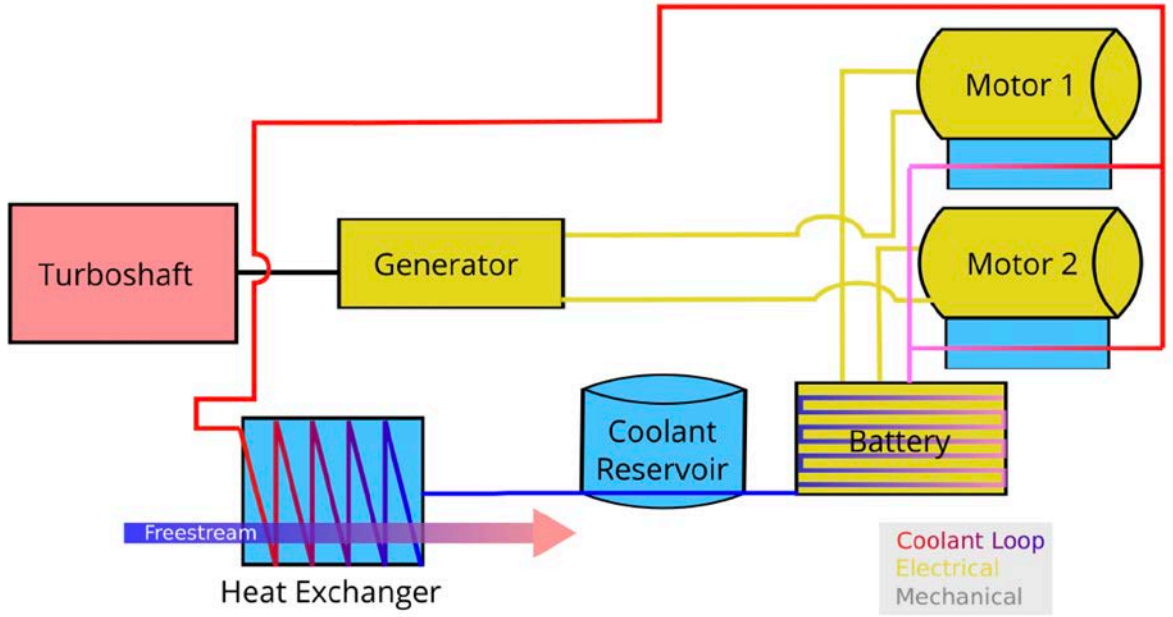
Jasa, et al., 2018

Findings support previous conclusions by Bergholz and Hitch (1992).

PTMS models used in optimization are comparatively simple.



Jasa et al., 2018



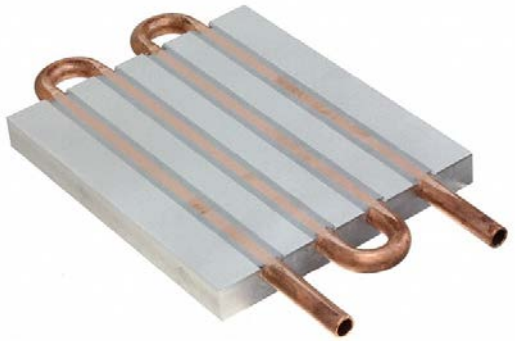
Brelje et al., 2019 [OpenConcept]

Models also do not include feedback controllers typically found in realistic systems.

Tool Development

Existing PTMS Tools

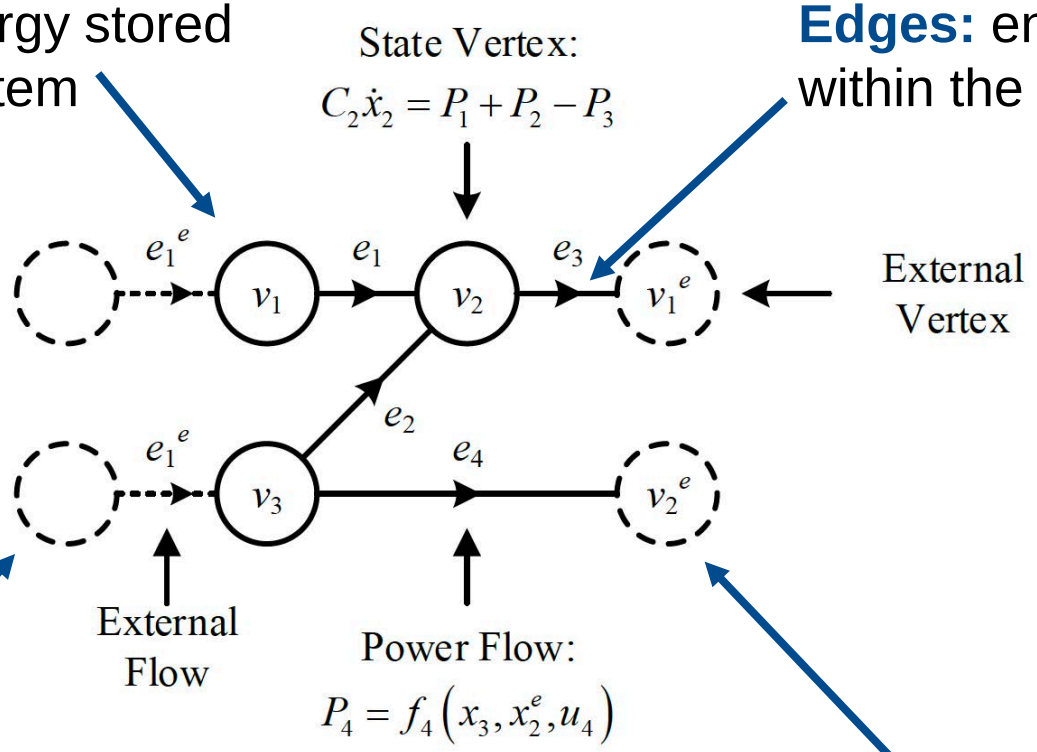
- Academia
  - Graph-based models
    - Complex systems
    - Have not provided gradients
  - Optimization-based tools
    - Python/OpenMDAO
    - Simple systems
    - Provide gradients for optimization
- Industry
  - Simulink/Matlab-based
  - Allow creation of complex subsystems
  - Do not provide gradients



Graph models are based on energy conservation laws.

Vertices: energy stored within the system

Edges: energy moving within the system

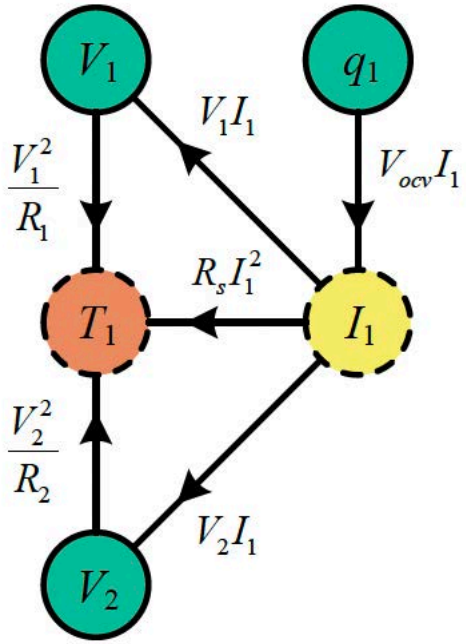


Sources: energy entering the system

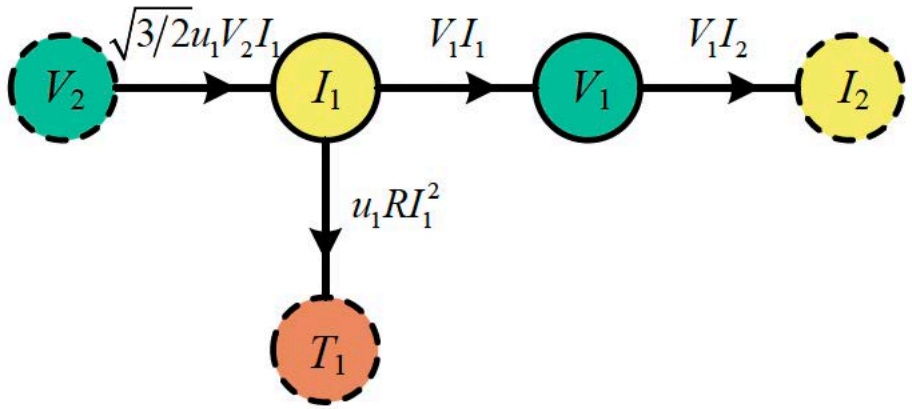
Sinks: energy leaving the system

Williams, M.A., et al., "Dynamical Graph Models of Aircraft Electrical, Thermal, and Turbomachinery Components," *ASME JDSMC*, 2018.

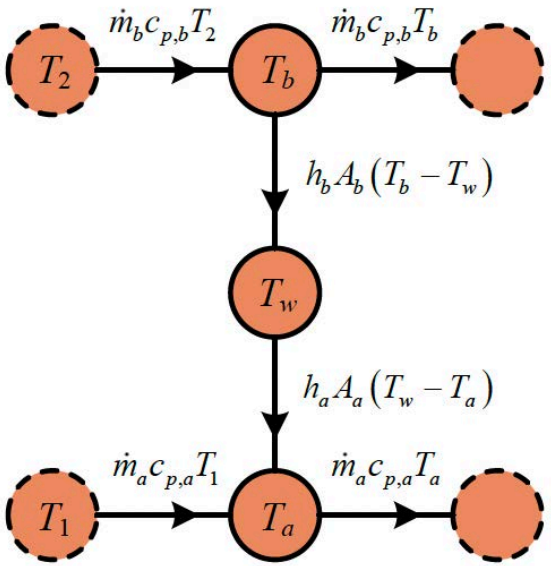
Graph-based components



Battery

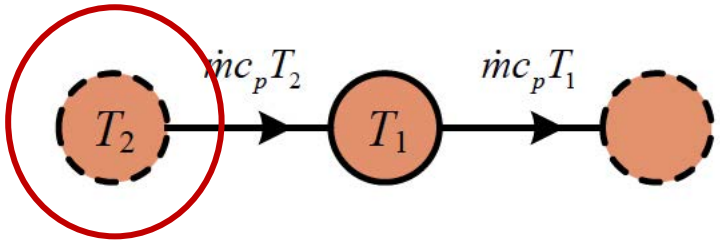


Inverter

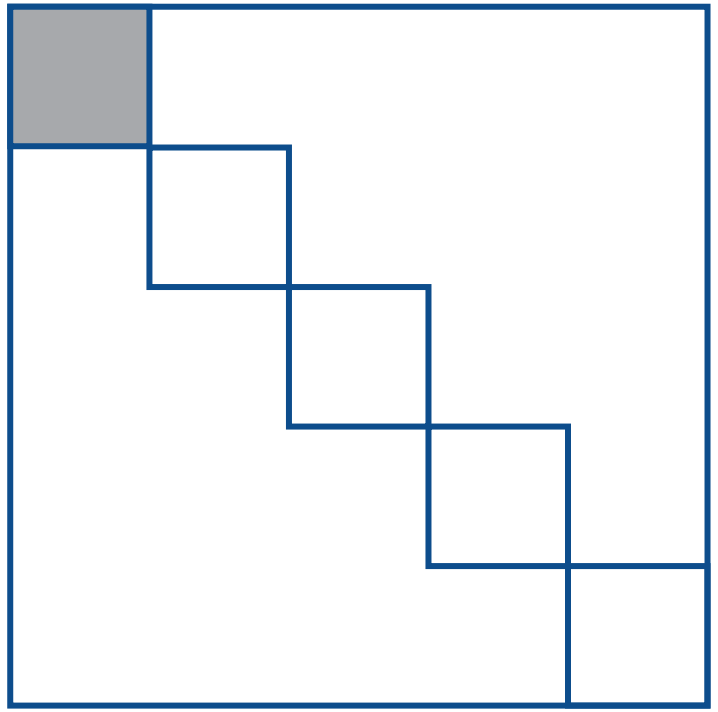


Heat Exchanger

Initial tool implementation

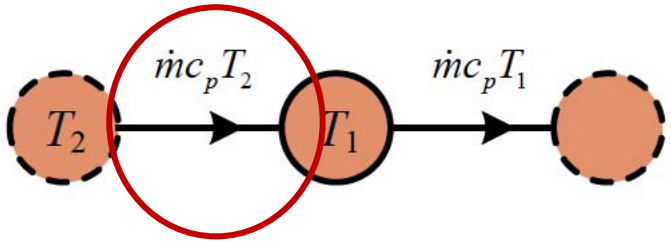


Fluid Tank

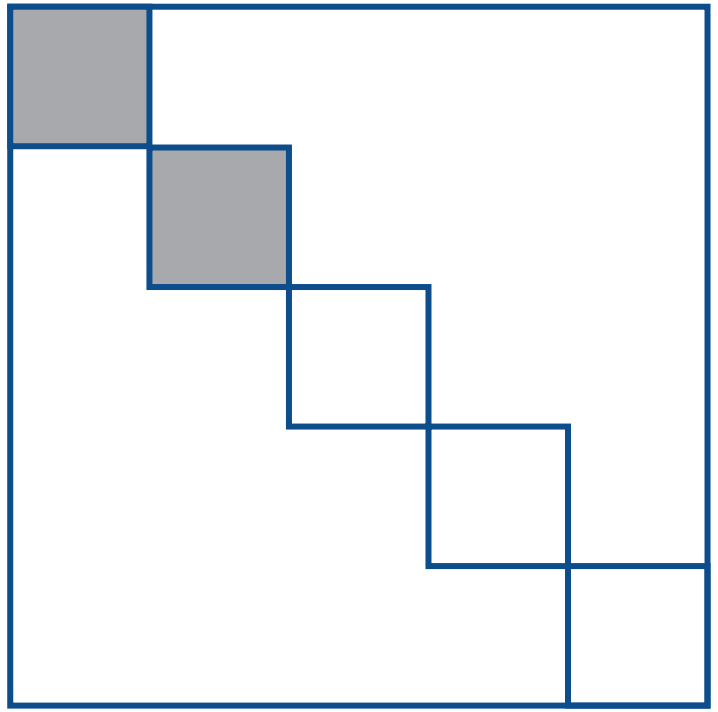


OpenMDAO representation

Initial tool implementation

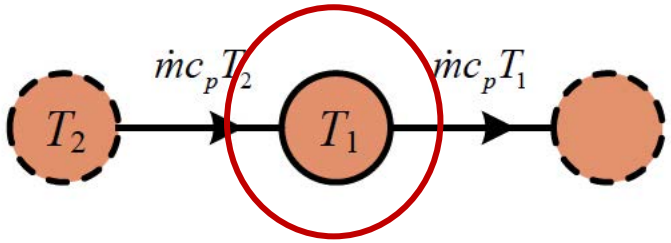


Fluid Tank

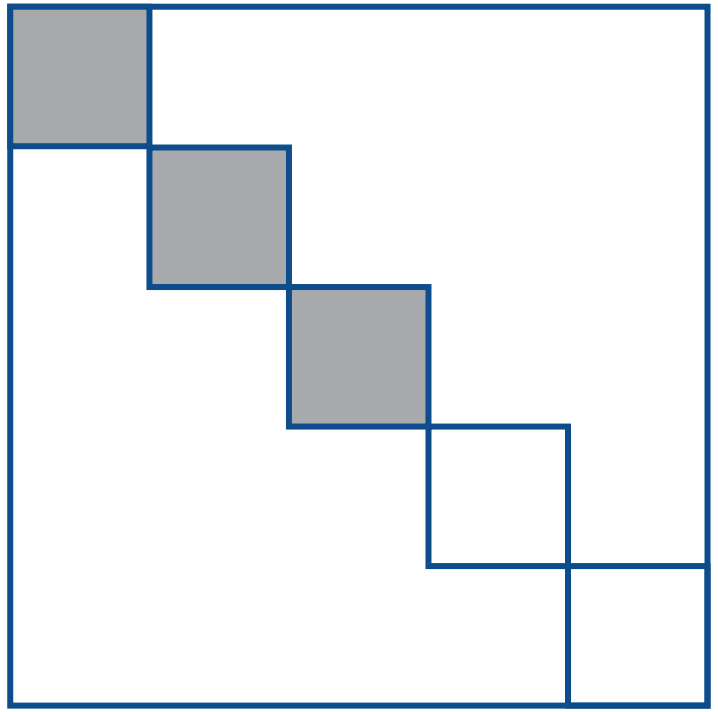


OpenMDAO representation

Initial tool implementation

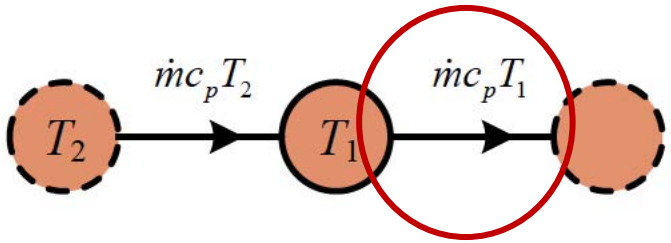


Fluid Tank

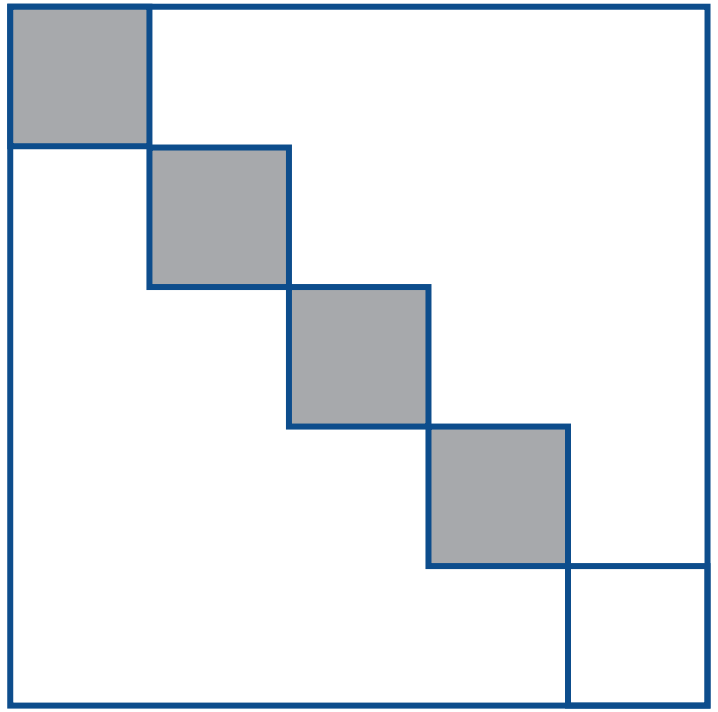


OpenMDAO representation

Initial tool implementation

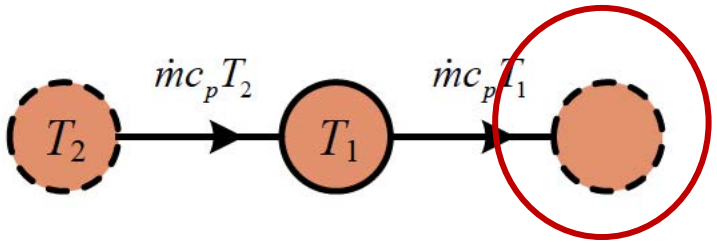


Fluid Tank

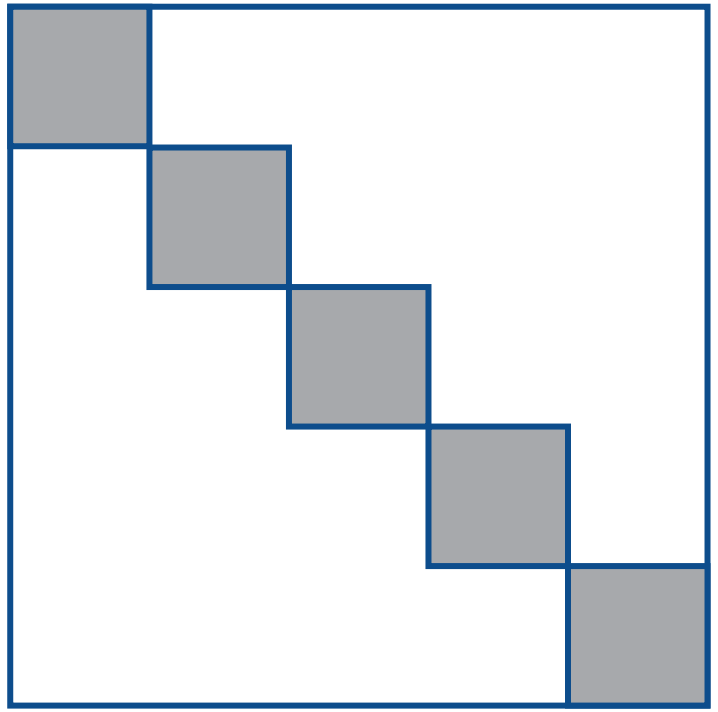


OpenMDAO representation

Initial tool implementation

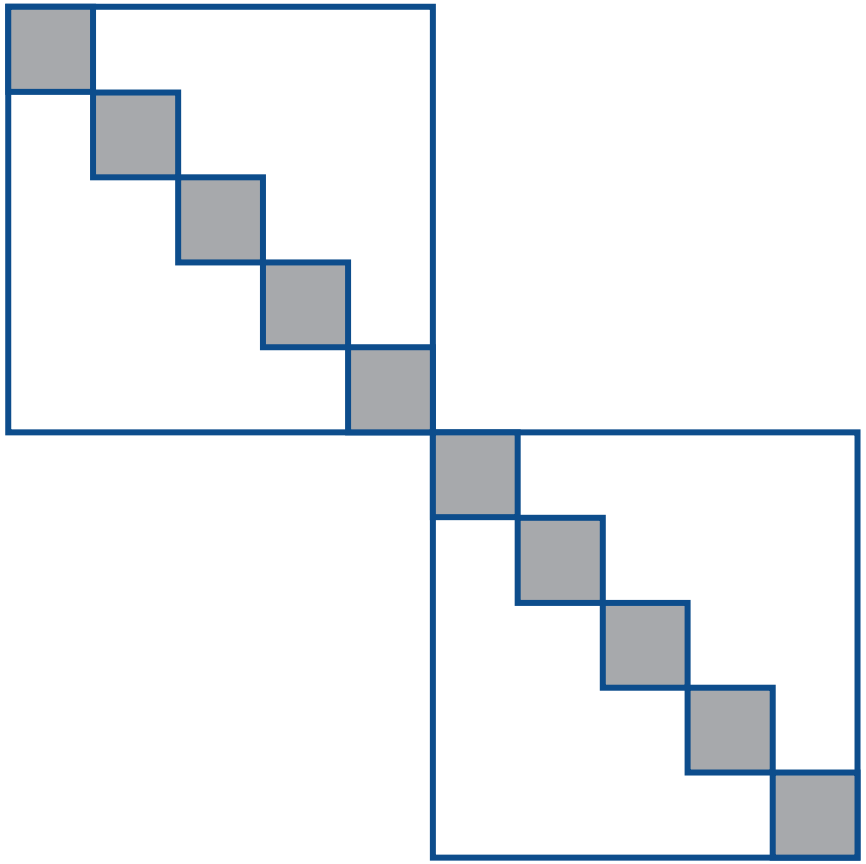


Fluid Tank



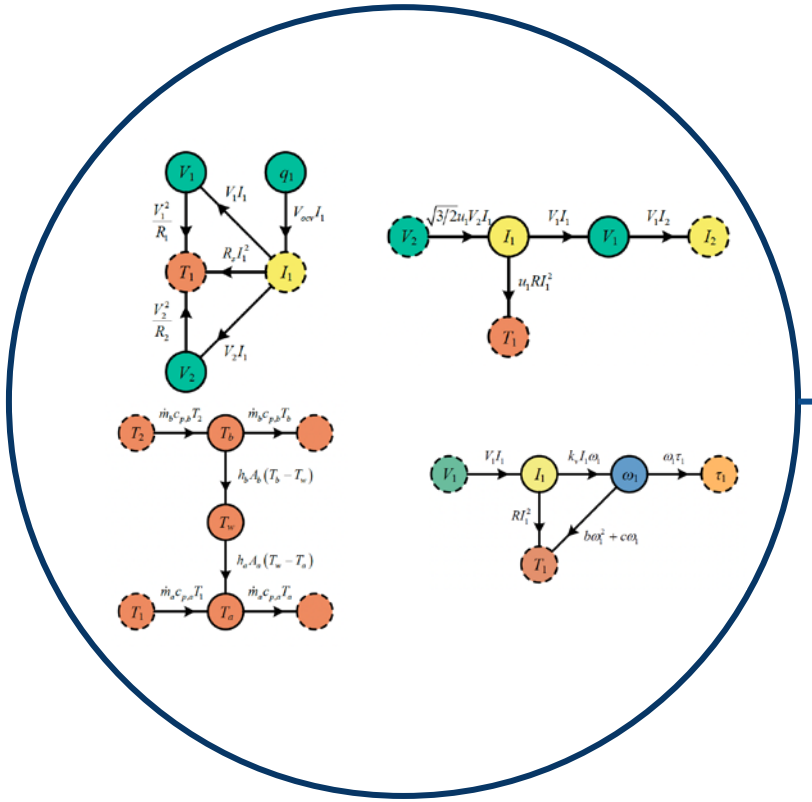
OpenMDAO representation

Initial tool implementation



Multiple PTMS components assembled together into a system

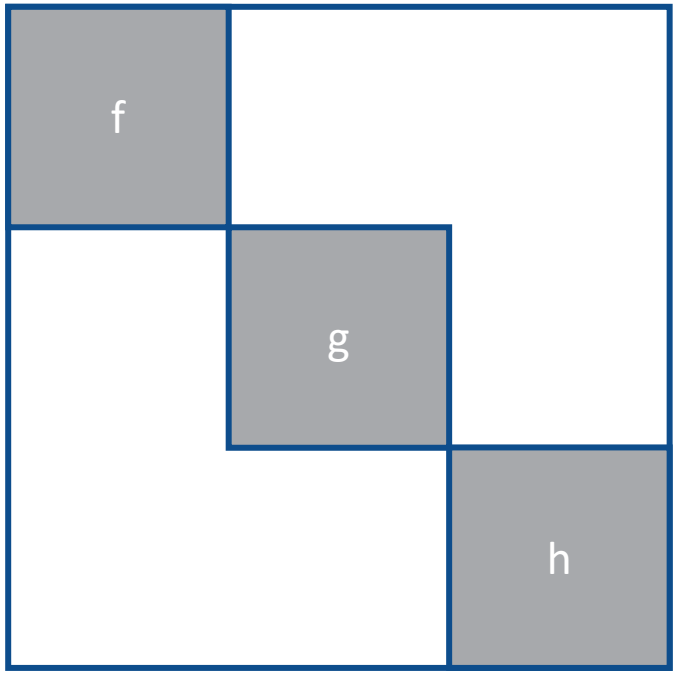
Revised Approach



System definition (Matlab)

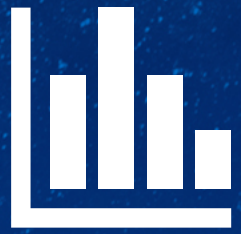
Code Generation

functions, partials, metadata

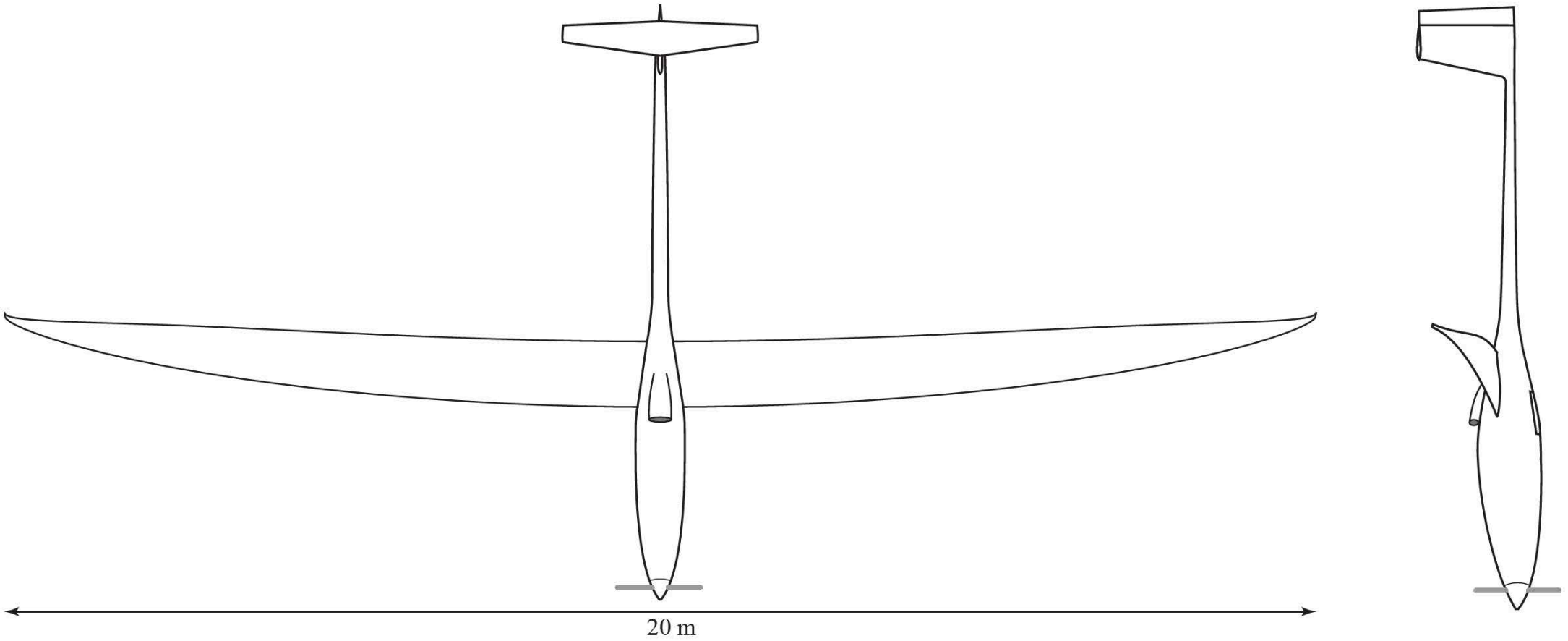


OpenMDAO representation

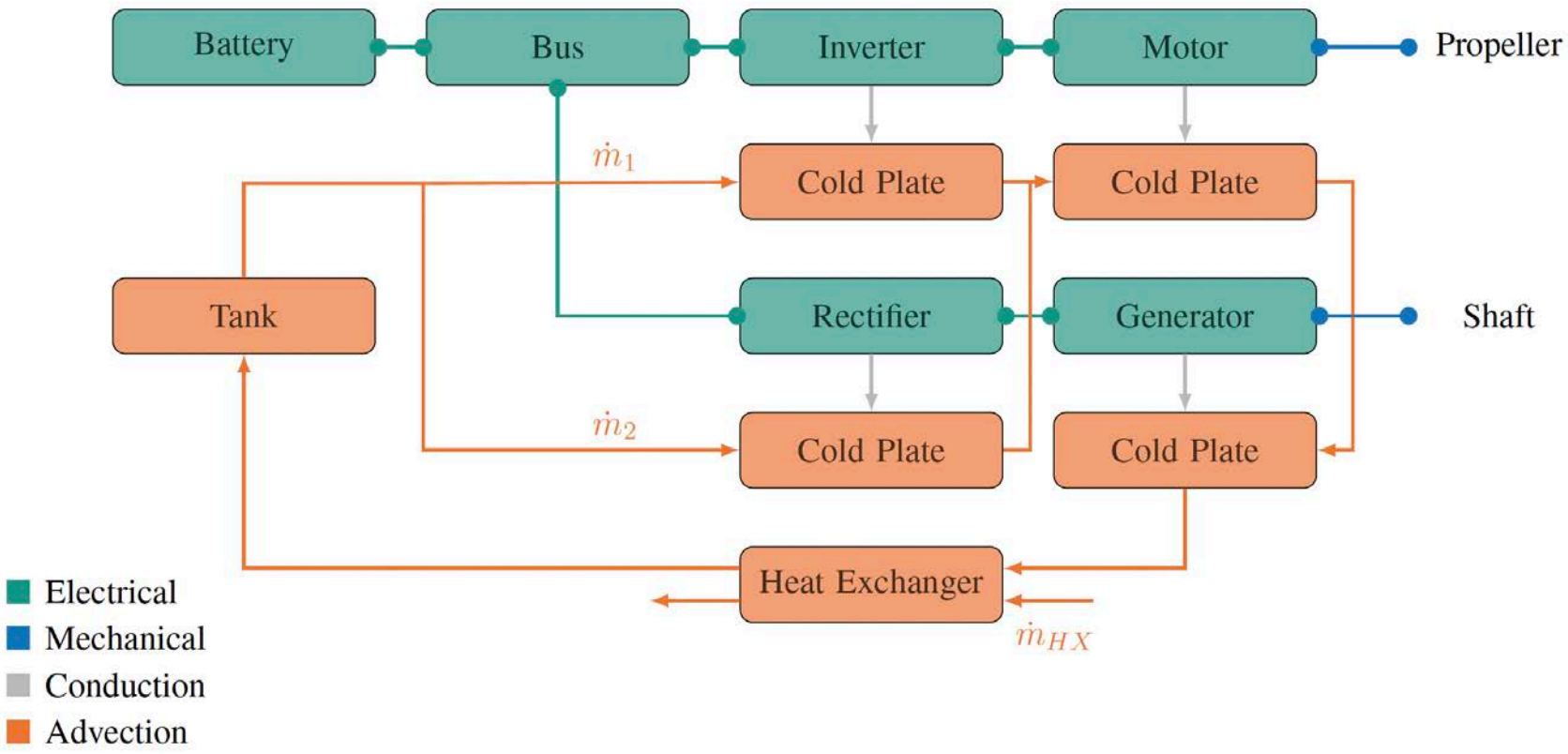
Studies



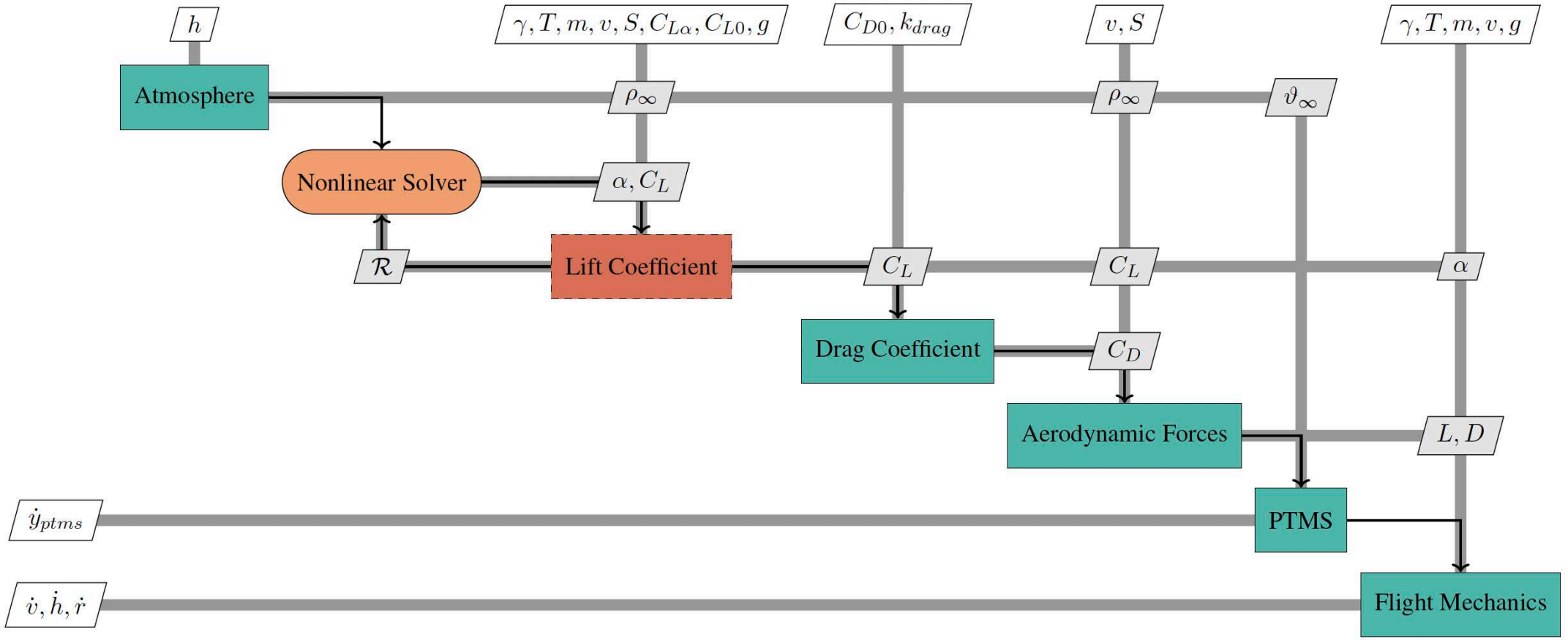
Notional Vehicle



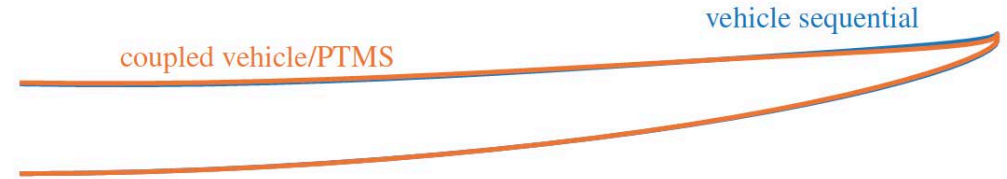
Series Hybrid System

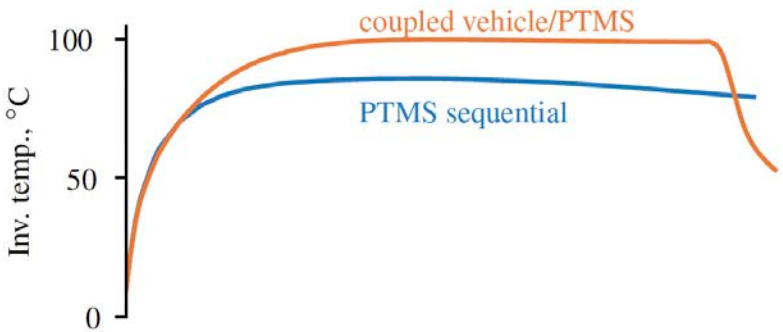


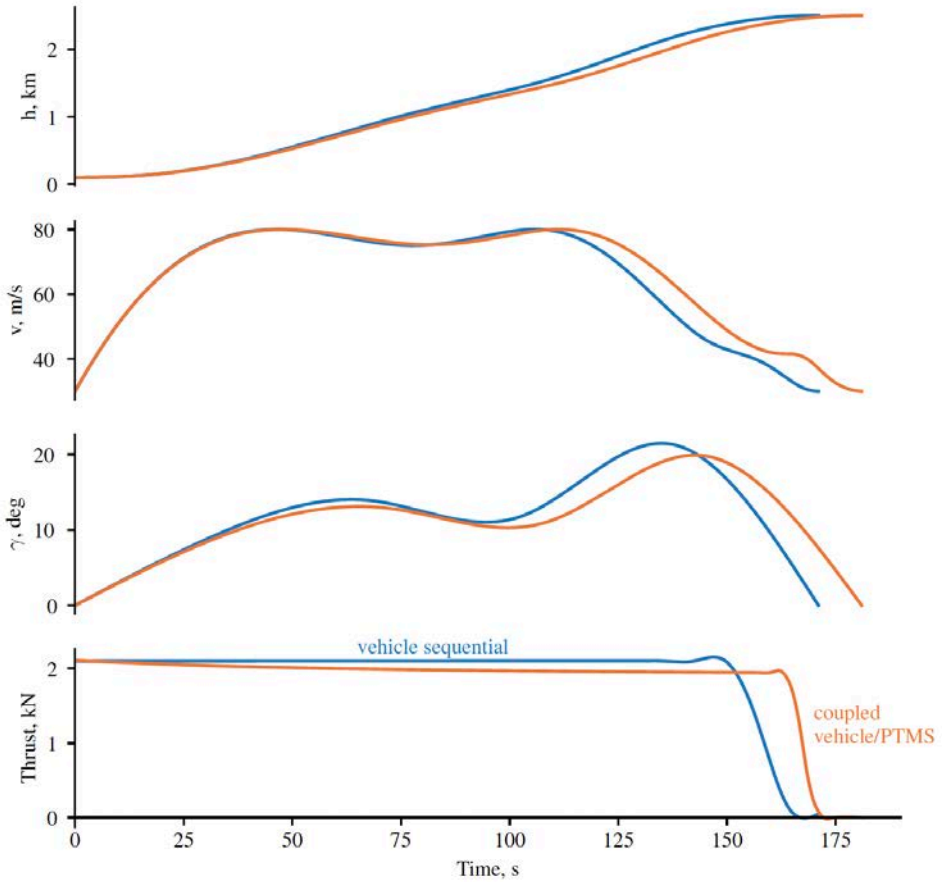
Tightly Coupled ODE



Vehicle/Sub-system Co-Design

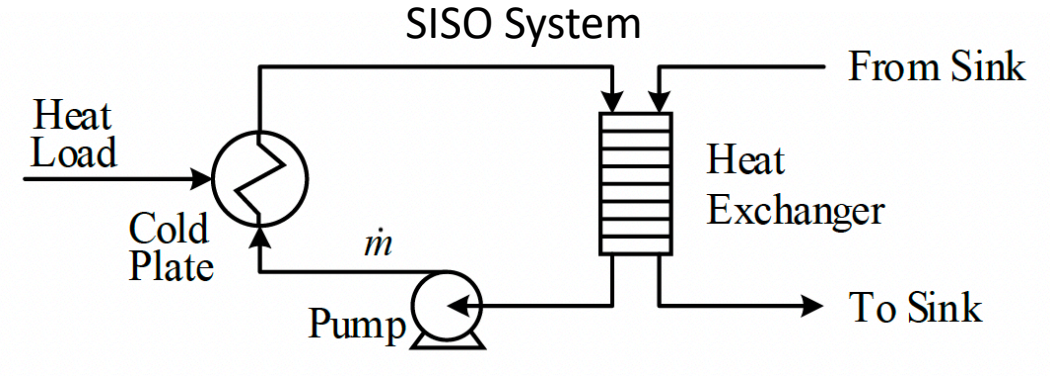


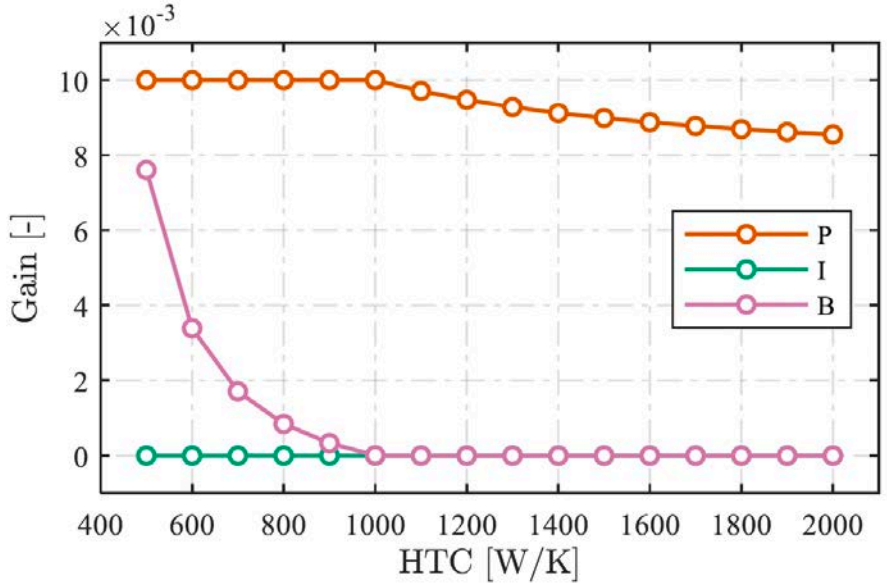


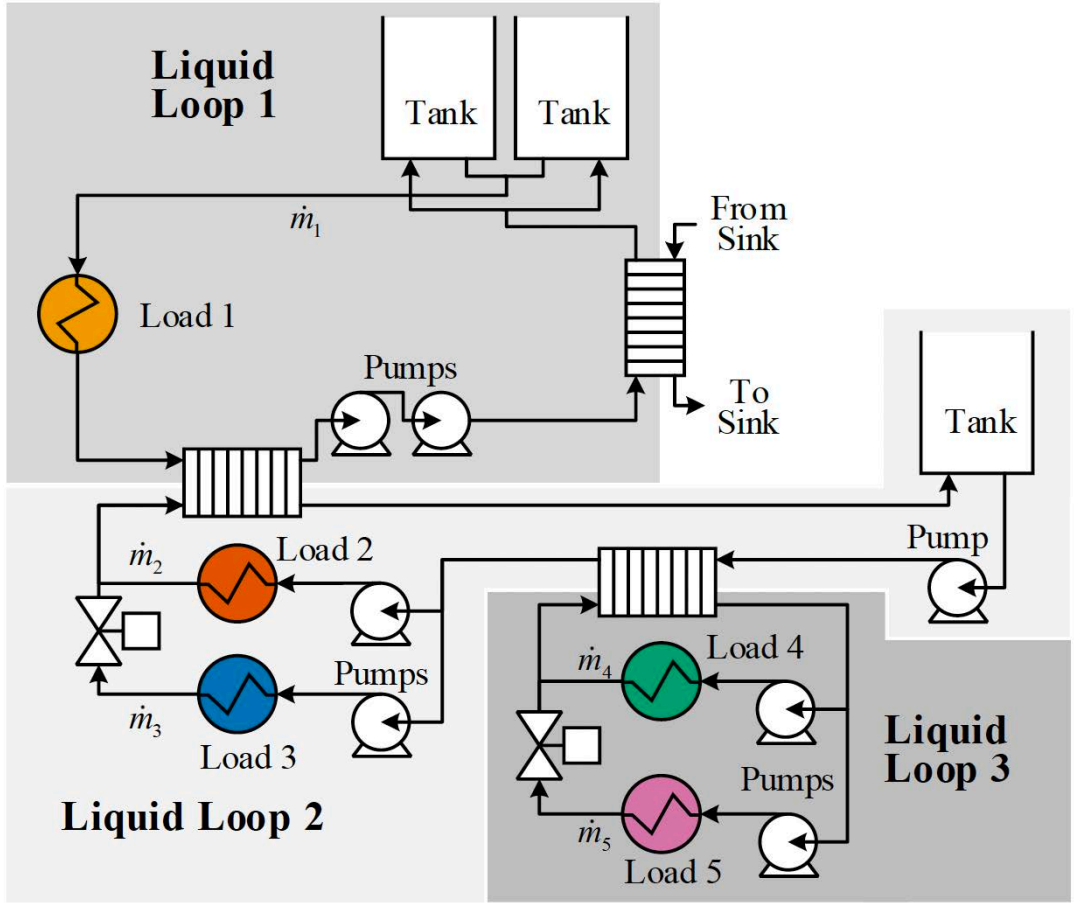


Lupp, C. A., Clark, D. L., Aksland, C. A., and Alleyne, A. G. “Mission and Shape Optimization of a HALE Aircraft Including Transient Power and Thermal Constraints.” In *AIAA AVIATION 2022 Forum*. Chicago, IL & Virtual: American Institute of Aeronautics and Astronautics, 2022.

Feedback Controller Sizing



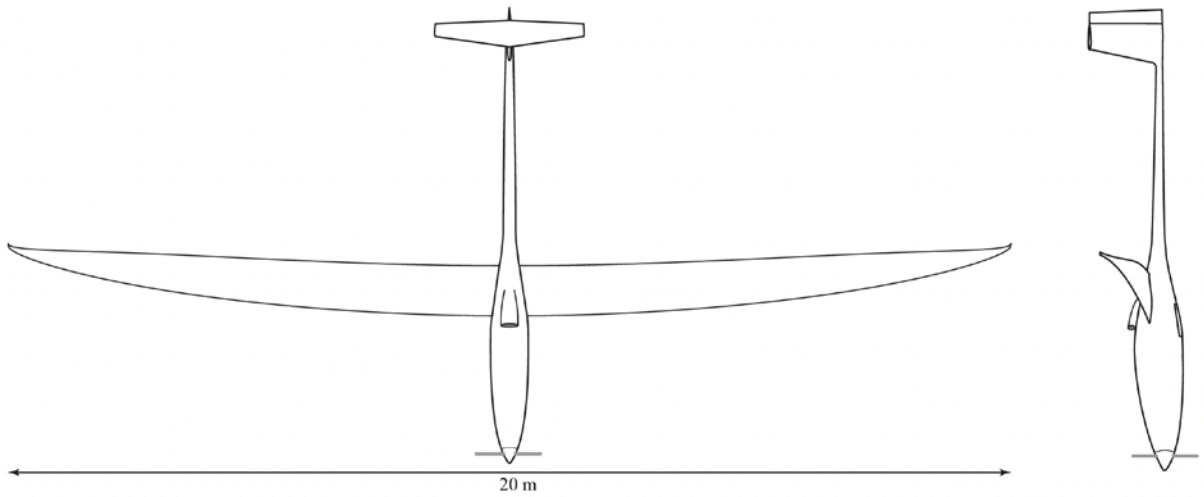


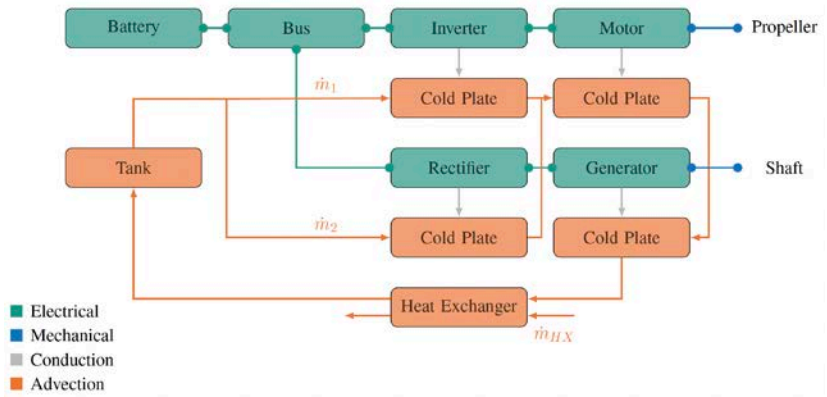


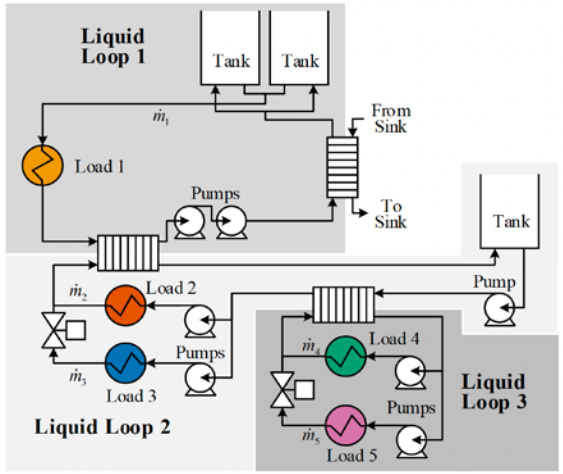
MIMO System

Aksland, C. T., Lupp, C. A., Clark, D. L., Alleyne, A. G. “Gradient-Based Optimization for Anti-Windup PID Controls,” Atlanta, GA. 2022.

Vehicle/Subsystem/Controller Co-Design



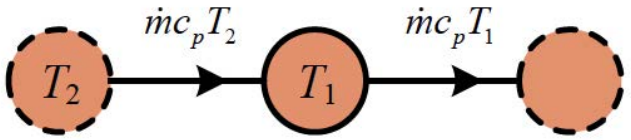


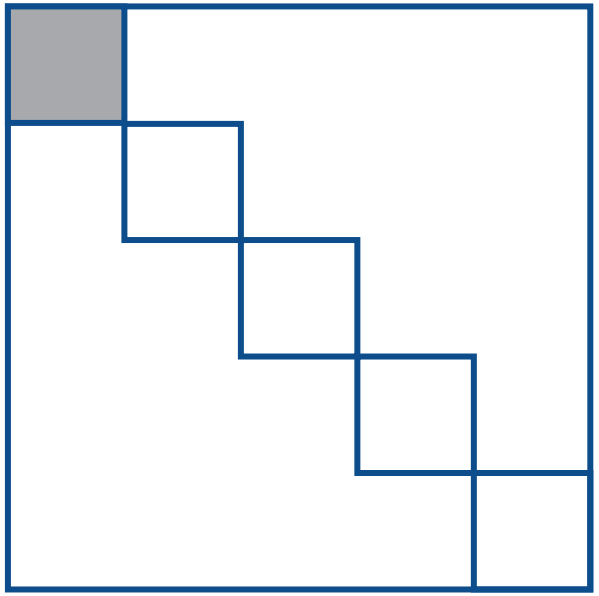


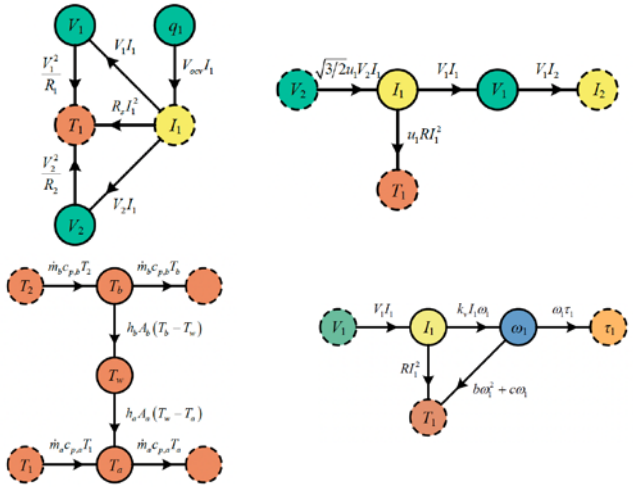
Lupp, C. A., Clark, D. L., Aksland, C. T., Alleyne, A. G. “Coupled Aerodynamic Shape, Mission, Power and Thermal Subsystem, and Feedback Controller Optimization for a HALE Vehicle,” SciTech 2023.

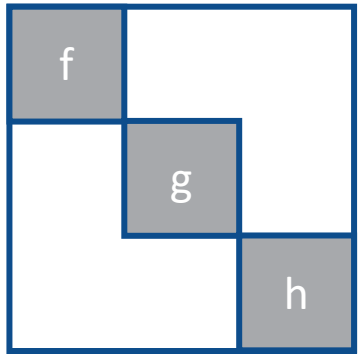
Concluding Remarks

Tool Development



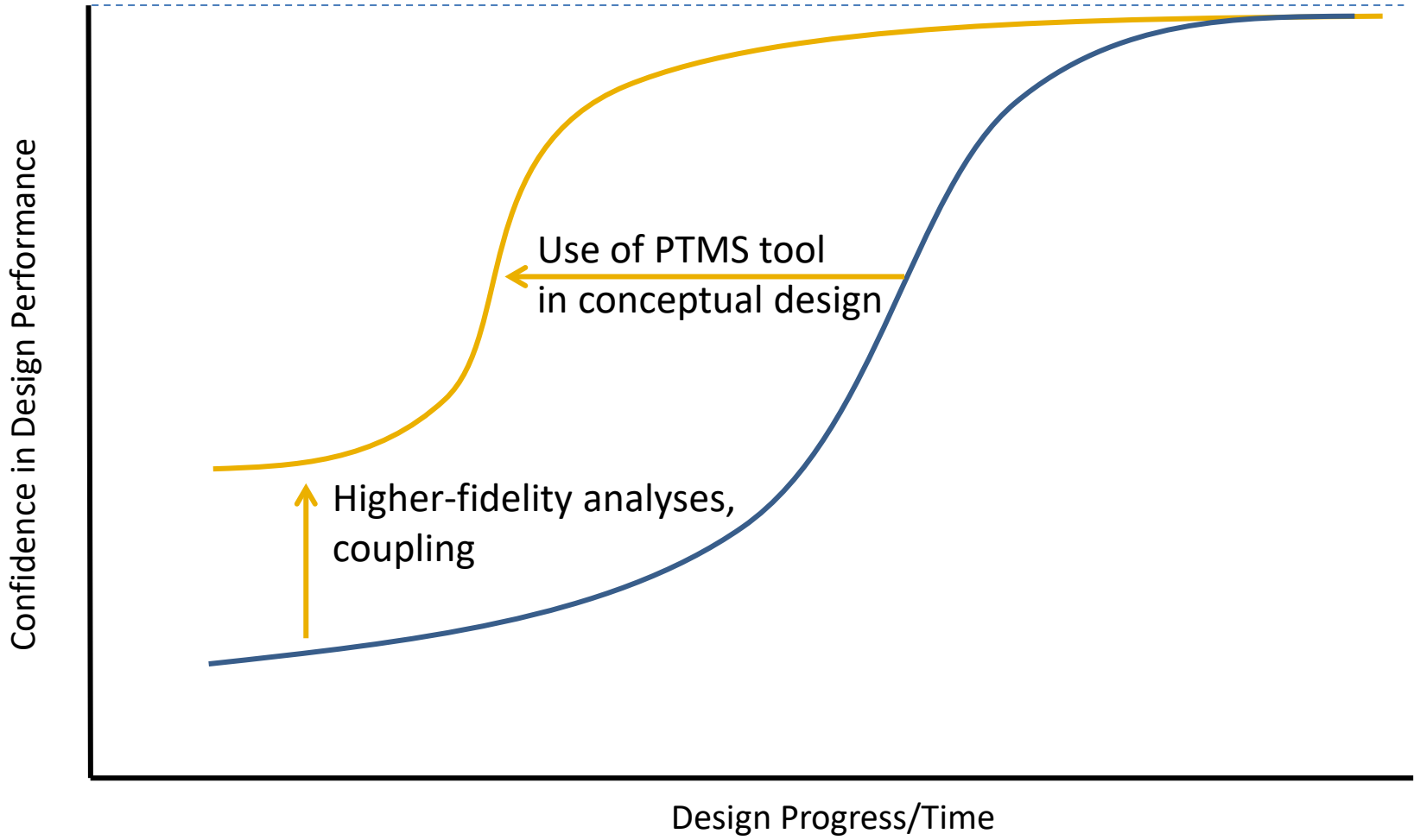






Small components may be easier, but come at a substantial performance cost.

Contributions to Vehicle Design



Questions