Hierarchical Control Co-Design (CCD) for Thermal-Fluid Systems

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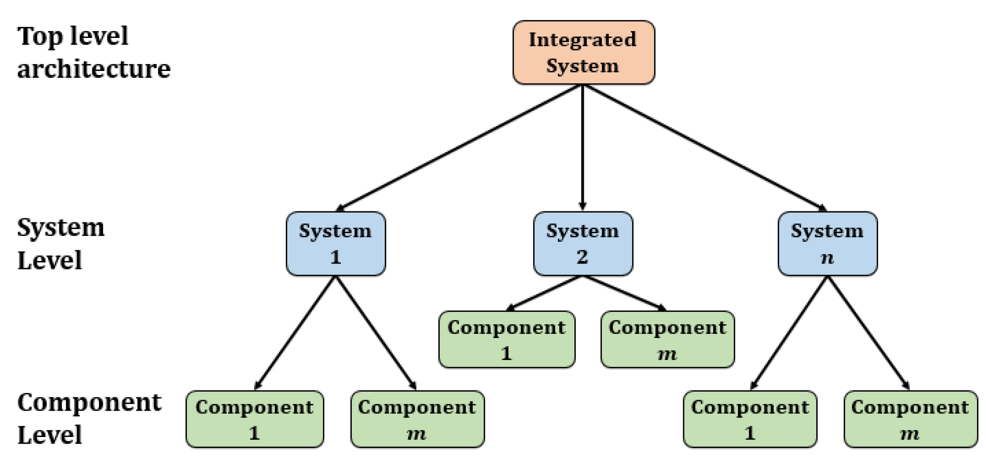
Problem Statement

As technological advances create the need for complex integrated systems, a new design paradigm is needed to realize the demands of next generation systems

Control co-design (CCD) offers a chance to reimagine the way in which we design complex systems

CCD requires a reduced-order model of the system dynamics

Detailed design decisions should be coordinated across a hierarchy to ensure optimal transient system operation



General System Hierarchy

Overall Research Objective:

Develop a new design approach for complex systems by merging the concepts of hierarchical (integrated) design optimization and CCD to develop a novel hierarchical CCD algorithm

Approach

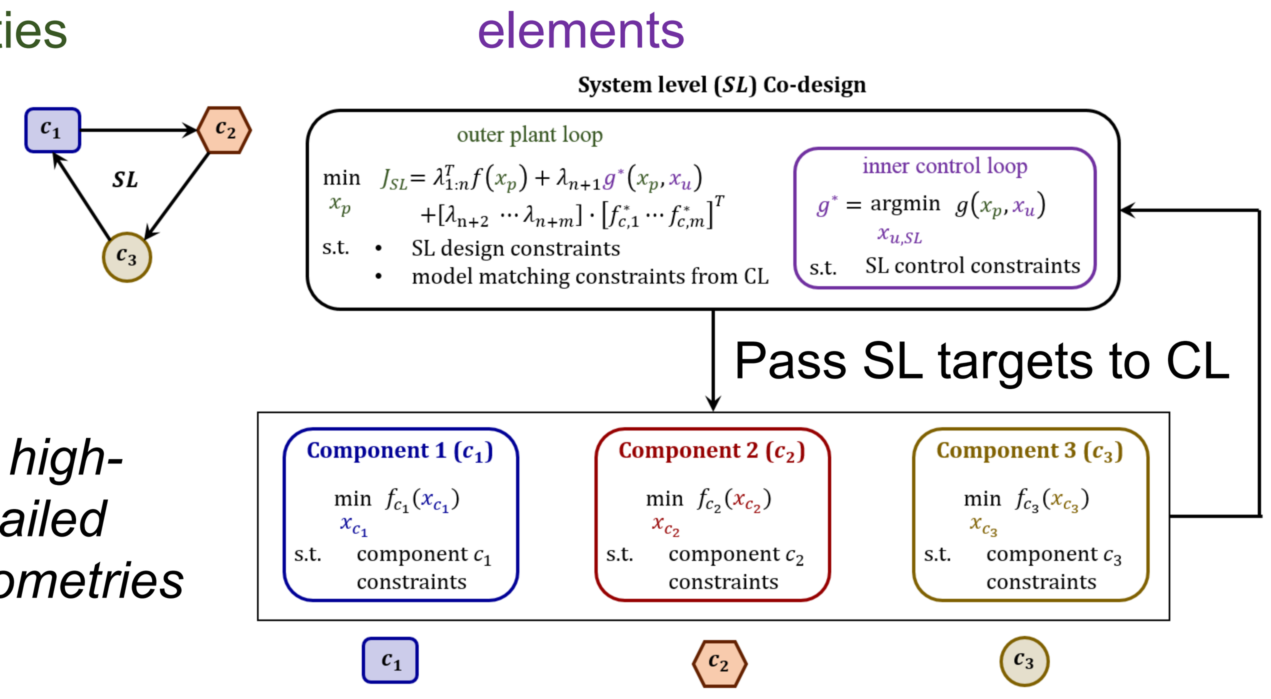
Our research focuses on thermal-fluid systems; however, the concept of hierarchical CCD can be applied to any complex system

SL outer loop optimizes *steady-state performance* and system design properties

SL inner loop optimizes *transient performance* and feedback control elements

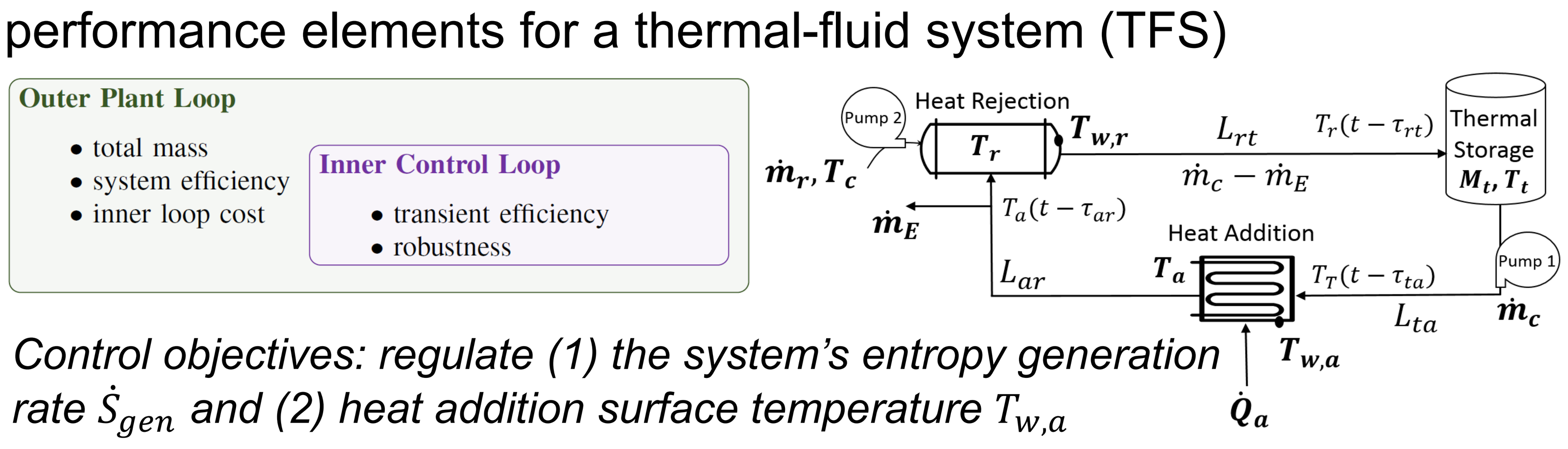
SL model is low-fidelity, or reduced order

CL models are high-fidelity with detailed component geometries



Pass optimal components back up to SL

1.) Design a system level (SL) nested co-design algorithm to optimize performance elements for a thermal-fluid system (TFS)

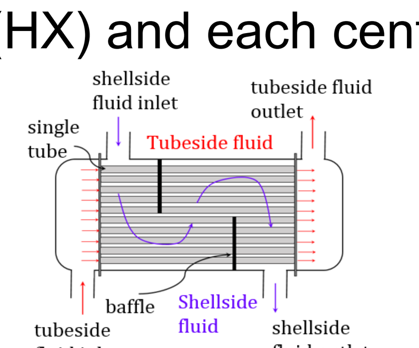


Control objectives: regulate (1) the system's entropy generation rate $\dot{S}_{gen}$ and (2) heat addition surface temperature $T_{w,a}$

2.) Develop design-only component level (CL) optimizations for a shell and tube heat exchanger (HX) and each centrifugal pump in the TFS

HX Optimization

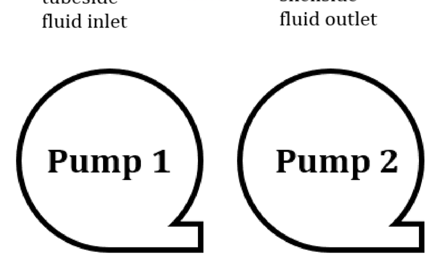
- HX mass
- HX footprint
- speed of heat rejection



Dynamic HX optimization uses model's eigenvalues to optimize transient performance in addition to design properties

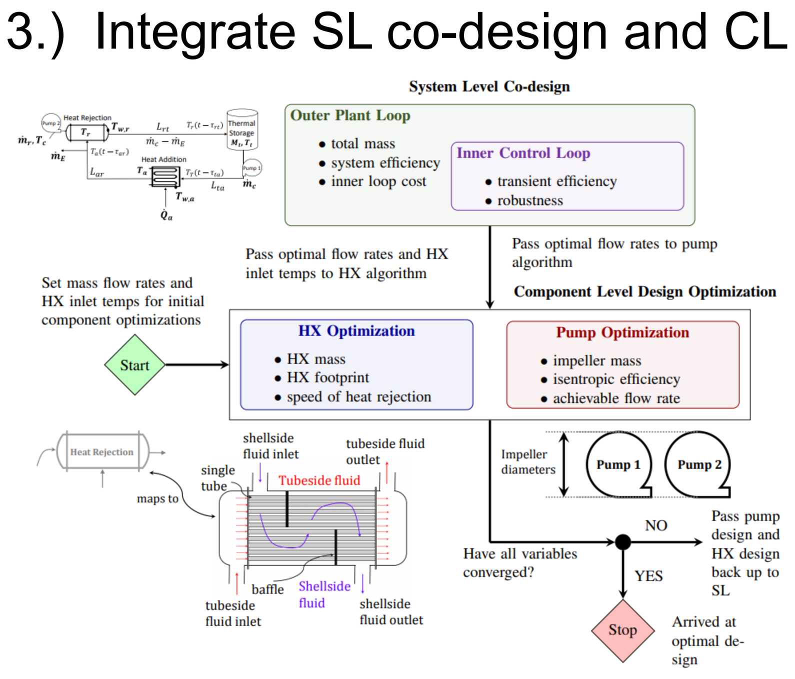
Pump Optimization

- impeller mass
- isentropic efficiency
- achievable flow rate



Static pump optimization selects pumps to operate near a best efficiency point while nominally operating at desired flow rates

3.) Integrate SL co-design and CL design optimization algorithms



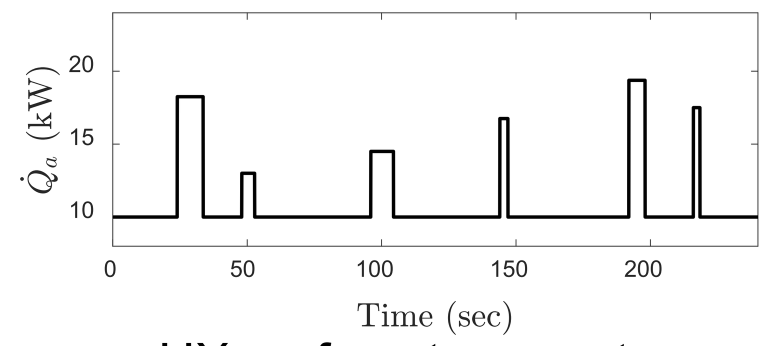
SL co-design algorithm ensures components are connected and operated to optimally to achieve specified performance objectives

CL design algorithms provide a method of selecting physically-tractable components that can be controlled in an optimal manner within an integrated system

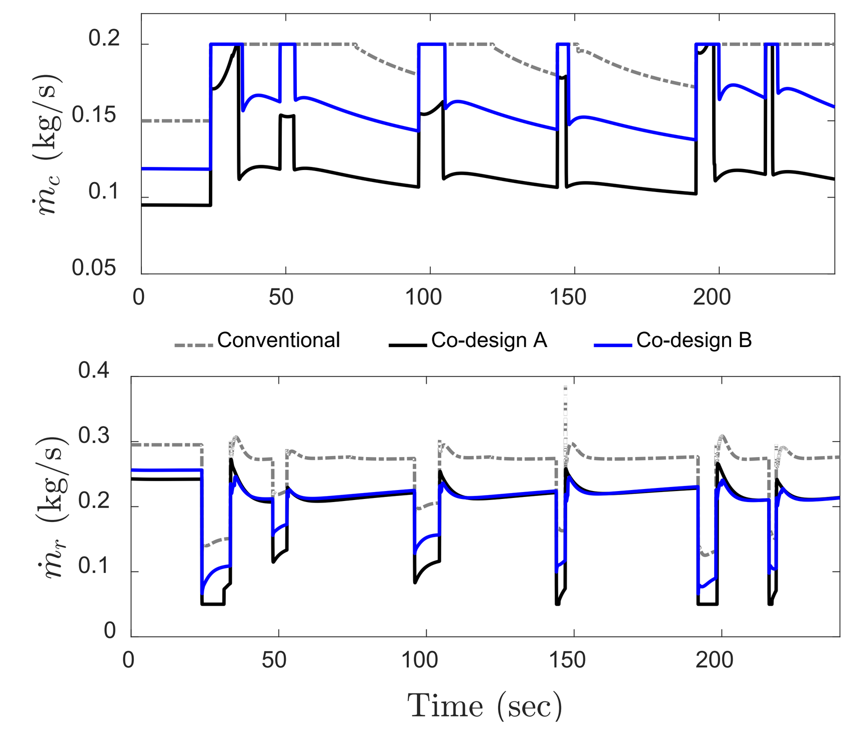
Results

System Level: CCD vs. Conventional Design for a thermal-fluid system

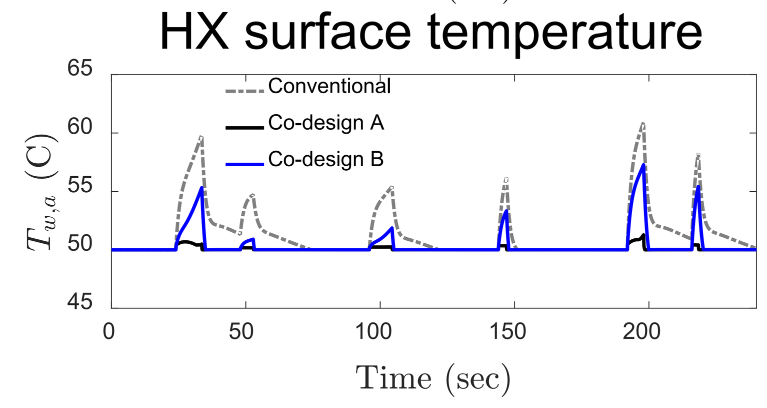
Heat load disturbance



Primary (top) and secondary (bottom) mass flow rates

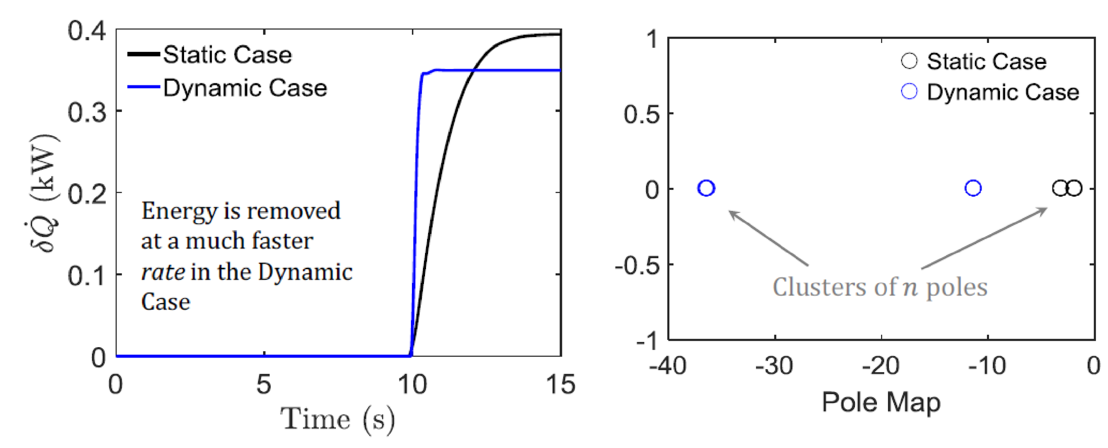


HX surface temperature



The co-designed systems are more robust to transient disturbances that are common to thermal-fluid systems

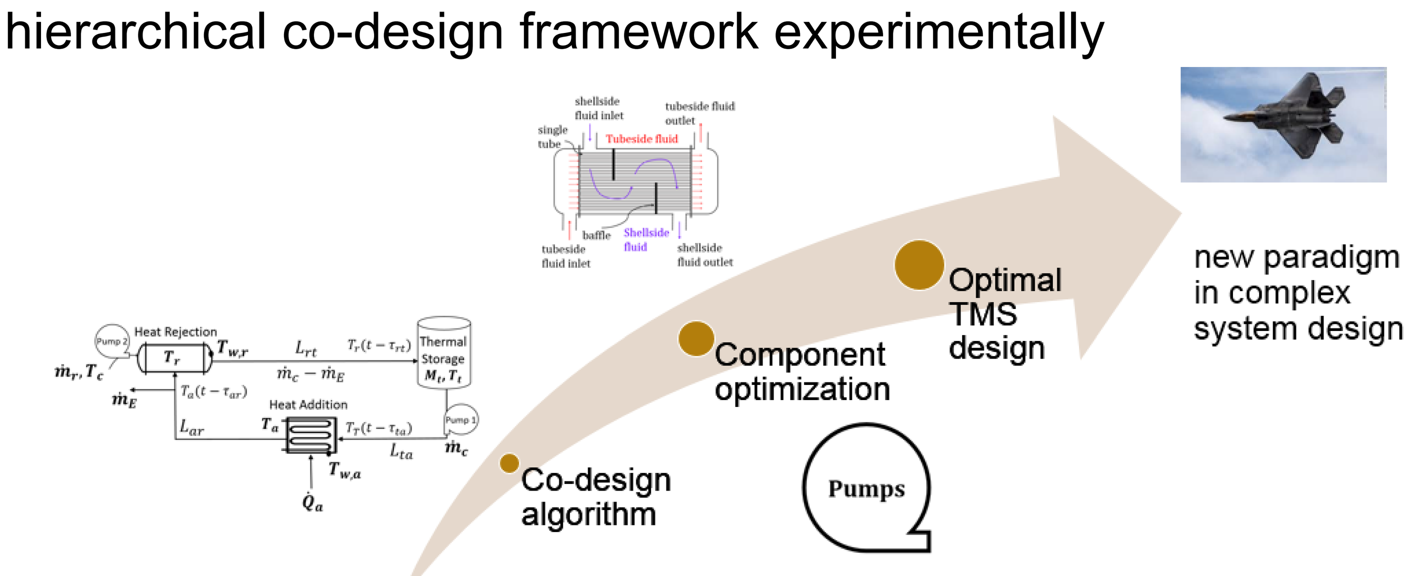
Component Level: Dynamic HX optimization offers improved *transient* performance compared to conventional methods



The heat removal time constant is 4x faster in the dynamic case

Future Work

Our future work involves building an optimal TMS and validating the hierarchical co-design framework experimentally



Publications

J1. A. Nash and N. Jain, "Hierarchical Control Co-design Using a Model Fidelity-Based Decomposition Framework." *ASME Journal of Mechanical Design.* Under Review.

J2. A. Nash and N. Jain , "Combined Plant and Control Co-design for Robust Disturbance Rejection in Thermal-Fluid Systems." *IEEE Transactions on Control Systems Technology*, Aug. 2019. DOI: 10.1109/TCST.2019.2931493.

C1. A. Nash, and N. Jain , "Dynamic Design Optimization for Thermal Management: A Case Study on Shell-and-Tube Heat Exchangers." *Proceedings of the 2019 ASME Dynamic Systems and Control Conference*, Park City, UT, Oct. 8-11, 2019.

C2. A. Nash and **N. Jain** , "Second Law Modeling and Robust Control for Thermal-Fluid Systems." *Proceedings of the 2018 ASME Dynamic Systems and Control Conference*, Atlanta, GA, Sept. 30 – Oct. 3, 2018.

Acknowledgements

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