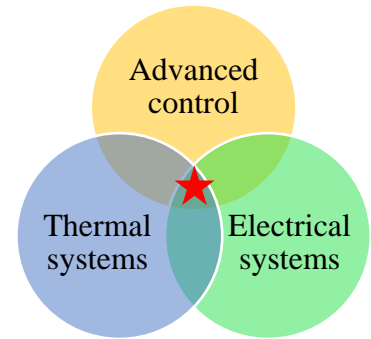


Advanced Control of Electro-Thermal Systems

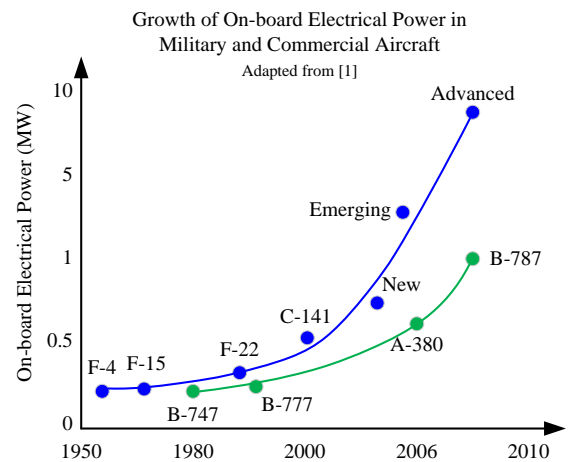
Introductory Statement

My research focus is on the coordination of thermal and electrical systems through advanced model-based control. My goal is to maximize the power density of these systems while maintaining safe and reliable operation, enabling significant technological advances in a wide range of current and future energy systems.



Research Need

Electrification of power systems is a societal megatrend, especially for vehicle systems such as aircraft, on- and off-road vehicles, and ships. For example, the onboard power for both military and commercial aircraft has grown rapidly over the last several decades (see Figure) and this growth is expected to accelerate, with an anticipated order-of-magnitude increase in power over the next 10 years [1]. With the majority of this power dedicated to onboard electrical systems, managing the heat generated by these systems has already become a major barrier. In fact, over 50% of military electronics failures are attributed to thermal management problems [2]. Electrification, and the resulting thermal management challenge, is also widespread in the commercial sector. The need for improved thermal management is highlighted by a recent workshop on “Thermal Challenges in Next Generation Electronic Systems” supported by the major funding agencies NSF, ONR, and DARPA [3].



In the absence of costly system redesign, *cooperative control of electrical and thermal systems is the key to overcoming these barriers and maximizing the capability of these systems*. Due to the complexity of these systems, a distributed control approach is required; where various parts of the system are operated by dedicated controllers that coordinate to meet system-wide objectives. Such control approaches will not only increase the total power and power density of these systems, they will also make these systems easier, safer, and cheaper to operate. Technological growth is currently limited by inadequate thermal management and intelligent control is a crucial part of overcoming this barrier.

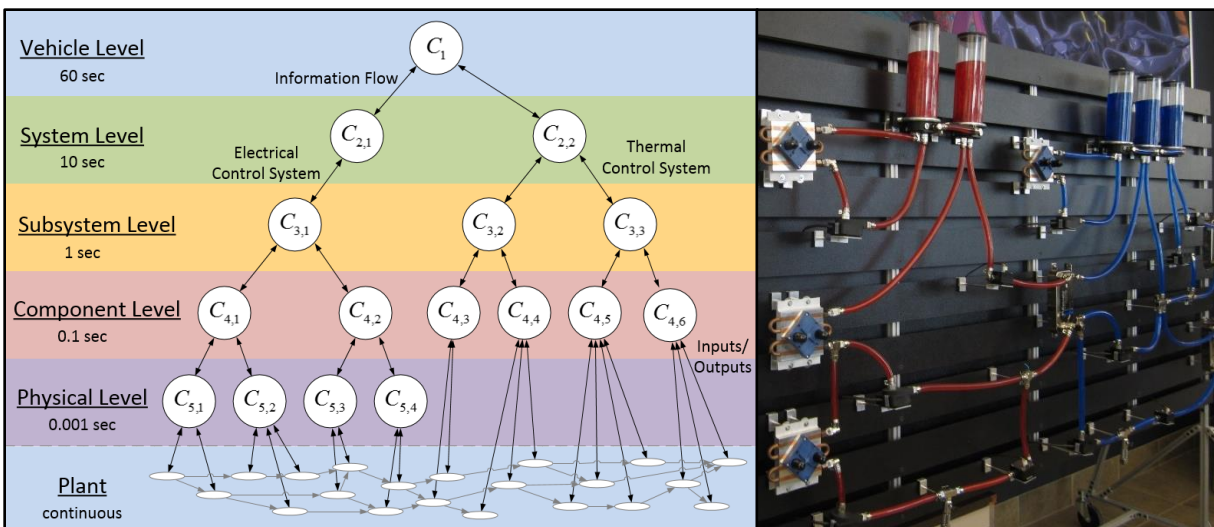
Core Research Objectives

My early career objective is to develop and demonstrate modeling and control tools that improve the performance and reliability of complex energy systems. These tools will facilitate coordination throughout the system, optimizing global objectives via localized decision and control. To achieve this goal, I will investigate the fundamental properties of modeling and control formulations, develop enabling technologies to bridge the gap between theory and application, and evaluate these developments on physical systems.

Research Accomplishments

Through my graduate research, I have developed a set of skills that make me uniquely capable of tackling these challenges. Through my Master’s work on the **modeling and control of large-scale multi-evaporator vapor compression systems for building systems**, I have developed expertise in control-oriented modeling of complex, nonlinear dynamic systems and decentralized **model predictive control (MPC)** to achieve superior performance and system efficiency using scalable, computationally-efficient control formulations [4]–[11].

Building upon this knowledge, my PhD research has focused on the development of a widely applicable, multi-level **hierarchical control** framework that strategically decomposes the system, and the corresponding control decisions, among many model-based controllers (see Figure). These controllers communicate to make coordinated decisions among the various components and subsystems over a range of timescales. I have designed and built a thermal-fluid experimental system (see Figure) to perform initial validation of this hierarchical control framework on hardware representative of a fuel thermal management system on an aircraft. This work has been supported by Phase I and II SBIR contracts with the Air Force Research Lab (AFRL) and the newly formed NSF Engineering Research Center (ERC) for Power Optimization of Electrical-Thermal Systems (POETS) directed by my advisor Dr. Andrew Alleyne at UIUC.



A number of enabling developments were made through these collaborations including:

- 1) a graph-based modeling framework for dynamic energy systems, capable of representing multiple interacting energy domains and timescales,
- 2) a generic N -level hierarchical controller formulation that employs MPC to make optimal control decisions [12]–[14], and
- 3) an experimental testbed that serves as a thermal equivalent to an electrical breadboard and enables the rapid development of thermal systems with various system architectures in order to evaluate the hierarchical control performance [15].

In addition to the practical development and implementation of the hierarchical control framework, I have also developed a set of **theoretical claims establishing stability and robust feasibility** of operational constraint for the closed-loop system under hierarchical control [16]–[18]. This work fills a large void in the current state-of-the art for hierarchical MPC. For vehicle systems in particular, guaranteeing safe and reliable operation is vital. A controller designed to ensure stability of the closed-loop system and prevent critical states (e.g. battery temperature) from exceeding critical bounds on safe operation is required for many high-performance, high-impact applications. Through my PhD work, I have investigated and demonstrated the potential benefits of graph-based modeling and hierarchical control approaches and these developments will serve as a springboard for future development.

Future Research Directions

In keeping with my core competencies of dynamic system modeling, hierarchical model-based control, and energy systems, I aim to build a research group with theoretical and application expertise in the rich area of dynamic energy system management.

Active Thermal Management – With the development of enhanced materials and engineered surfaces, the ability to remove heat from electronic devices has increased significantly over the past several decades [19], [20]. Many of these advancements would be considered *passive*, where the improved heat transfer is a result of greater thermal conductivity or overall convective heat transfer coefficient. Through collaboration, my research would go beyond these passive enhancements by developing and controlling *active* thermal management devices. Devices, such as thermal switches [21] and triggered nucleate boiling [22], provide novel opportunities to actively manage and route the flow of thermal energy. My intent is to use a strategic combination of dynamic simulation and experimental hardware to understand the role of these devices in the operation of the larger thermal management system. I will leverage my background in graph-based dynamic modeling and MPC to determine how to best integrate and control active heat transfer devices within a system. This research will clearly demonstrate how effective control can lead to greater power densities and increased reliability of electronic devices.

Industry-Friendly Hierarchical Control – The development of model-based hierarchical control for complex, multiple-timescale systems is still in its infancy. While my PhD work focused on the development and analysis of an initial control framework, much work is still needed to produce a generic hierarchical control procedure that is highly practical and applicable. Major constraints, which have yet to be considered, are the computational and communication burdens of hierarchical control approaches. The control approach from my PhD was primarily focused on control performance and was performed in simulation, where computational resources were not a limiting factor. My intent is to develop and analyze alternative controller formulations that are designed specifically to minimize computational and communication costs for hardware implementation. I will leverage my existing hierarchical control framework to serve as a benchmark and utilize my control and experimental hardware background to develop alternative approaches tailored for computing hardware found in vehicle and mobile systems applications. This research will clearly demonstrate how computational resources affect achievable control performance for various control approaches.

Interdisciplinary Collaboration

Due to the interdisciplinary nature of this research, collaboration is key. Through previous and current collaborations within POETS and the AFRL programs, I have been a leading member of many interdisciplinary teams. One of the goals of POETS, is not just to develop interdisciplinary teams but to develop interdisciplinary individuals. As such, I have developed strong technical expertise in the areas of advanced modeling and control of thermal systems along with a breadth that allows me to see how my work relates to the larger picture and can benefit from the talents of others. I am eager to establish a research group with a strong focus on technical depth, superior communication, and effective collaboration with other researchers within the department and university.

Funding and Collaborative Opportunities

My proposed research plan will have technological impact at the intersection of several disciplines including thermal system design and operation, electrical system energy management, and control systems theory development and application. Research in this area is in high demand and I will seek funding from agencies including the Air Force Research Lab (AFRL), the Office of Naval Research (ONR), and the National Science Foundation (NSF), specifically programs such as Dynamics, Control and System Diagnostics (DCSD), Cyber-Physical Systems (CPS), and Energy, Power, Control and Networks (EPCN). I will also seek industrial collaboration through established contacts with Caterpillar, Ford, Champaign-Urbana Aerospace, and PC Krause and Associates. Finally, I will pursue a variety of young investigator honors such as the NSF CAREER Award, the Air Force Young Investigator Award, the ONR Young Investigator Award, and the DARPA Young Faculty Award.

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