Generating Design Knowledge Through Systematic Investigation of Interacting Physical Phenomena

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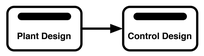
Integrated Physical and Control System Design

- Capitalizes on synergy between plant and control design

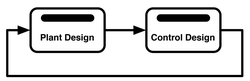
Design Process Options

Conventional Design Methods

Conventional Sequential Design

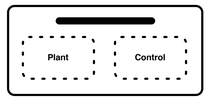


Iterated Sequential Design

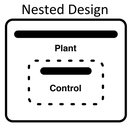


Co-Design

Simultaneous Design

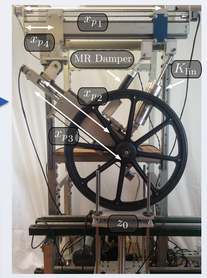


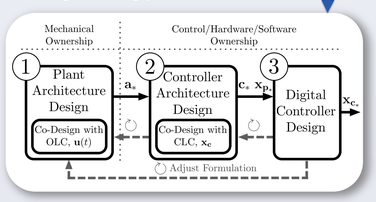
Nested Design



Recent co-design developments:

- Balanced co-design (comprehensive physical design)
- Co-design method validation via reconfigurable testbeds
- Steps toward integration with systems engineering processes





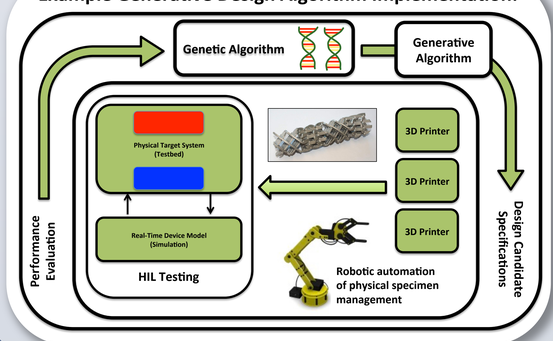
Generative Algorithm Design Abstractions

Indirect design representations: reduce problem dimension, manage variable dimension problems, targeted exploration

Generative design algorithms – established in art/architecture

- Based on simple **recursive rules** with **emergent properties**
- **Map** abstract design variables to complex system design descriptions
- For both **continuum systems** and **network design representations**

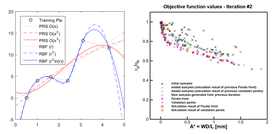
Example Generative Design Algorithm Implementation:



Framework for Extraction and Validation of Generalizable Design Knowledge from Systematically Generated Design Data

Design Data

- Systematic optimization studies
- Tradeoffs and performance limits
- Observational data
- Numerical and physical experiments



Analysis of Data

- Design properties
- Patterns and trends
- Explanatory analysis of behavior
- Extraction/formulation of generalizable design knowledge

Design Knowledge

- Generalizable, qualitative design insights and design principles
- More effective design heuristics

Design Knowledge Validation

- Definition of tests capable of disproving design principles, theories, or heuristics

- Perform additional numerical or physical experiments
- Update or formulate new design theories if disproven

Tools and methods to support design data generation

- New capabilities in design optimization
- Design of experiments for knowledge generation
- Modeling and simulation for design
- Incorporating physical experiments into design studies
- Validation of design methods and models

Optimization as an aid for design science: beyond identification of optimal designs

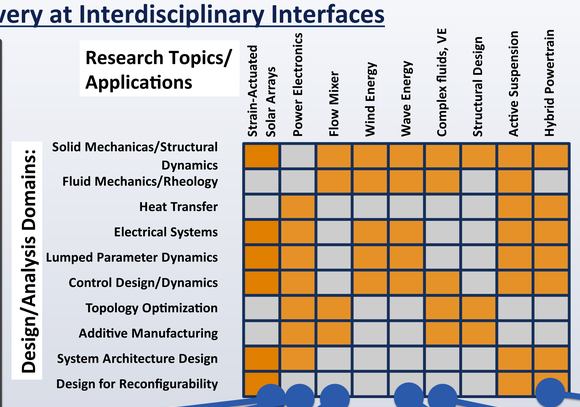
Research Strategy: Discovery at Interdisciplinary Interfaces

Primary Research Outcomes:

- Knowledge of how to combine interacting physical phenomena in new ways to create new technical capabilities
- Design exploration and optimization tools that accelerate design discovery

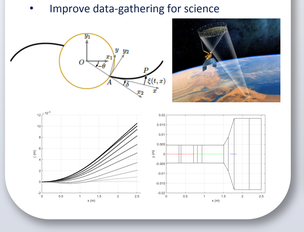
Applications:

- Focus on high-impact (infrastructure, transportation, energy, scientific discovery)
- Wide variety to support discovery of generalizable themes and access to a variety of interfaces

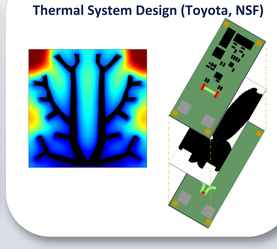


Strain-Actuated Solar Array (JPL/NASA)

- Dual-use of arrays (power, actuation)
- Improve data-gathering for science



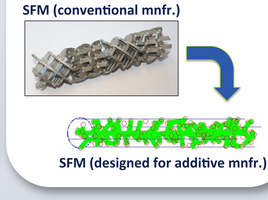
Combined Power Electronics and Thermal System Design (Toyota, NSF)



Static Flow Mixer Design (P&G)

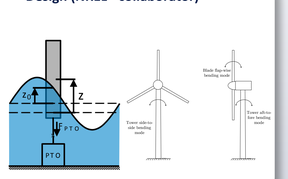
- Automated physical experiments in design optimization loop
- Design for additive manufacturing

SFM (conventional mnfr.)

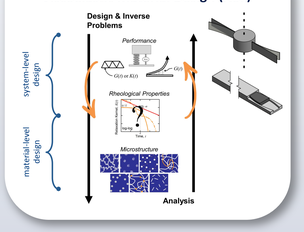


SFM (designed for additive mnfr.)

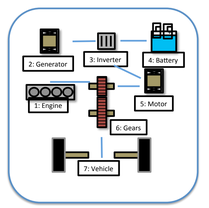
Wind and Wave Energy System Design (NREL - collaborator)



Rheologically Complex Fluid and Viscoelastic Material Design (NSF)



Hybrid Powertrain Architecture Design (Deere & Co.)



Selecting Effective Design Strategies

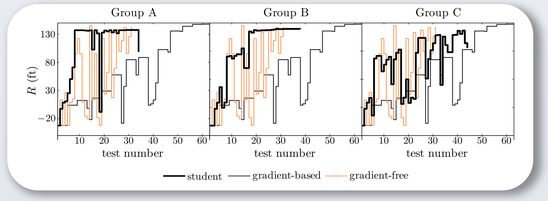
Rapid Heuristics ⟷ High-Fidelity Optimization

Range of design strategies available

- Evaluate tradeoff between fast heuristics and more accurate but time-consuming optimization methods (many options in between)
- Determine how to most effectively extend human design capability by selecting or constructing the most appropriate design tool
- Learn how to generate more effective heuristics from optimization results

Fusion between human and normative decision-making

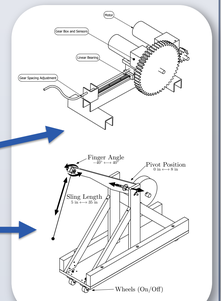
- Identify what decisions are best made by humans and those best made by design automation tools
- Plots below compare objective function improvement for trebuchet design problem between human designers and optimization algorithms



Design Education: K-12, University-Level, Industry

Streamlined hands-on activities for targeted design learning

- Facilitated by reconfigurable mechatronics systems, simulation tools
- K-12 outreach and undergraduate courses
- HIL Gear testbed linked to real-time vehicle simulation.
- Reconfigurable trebuchet activity with DOE, trebuchet physics, and multi-body dynamics models
- Bolted joint design and testing



Foundations for design Ph.D. students

- Consensus on core topics
- Develop short courses and universal design research foundations graduate course
- NSF NRT?