Integrated Physical and Control System Design for Horizontal Axis Wind Turbines

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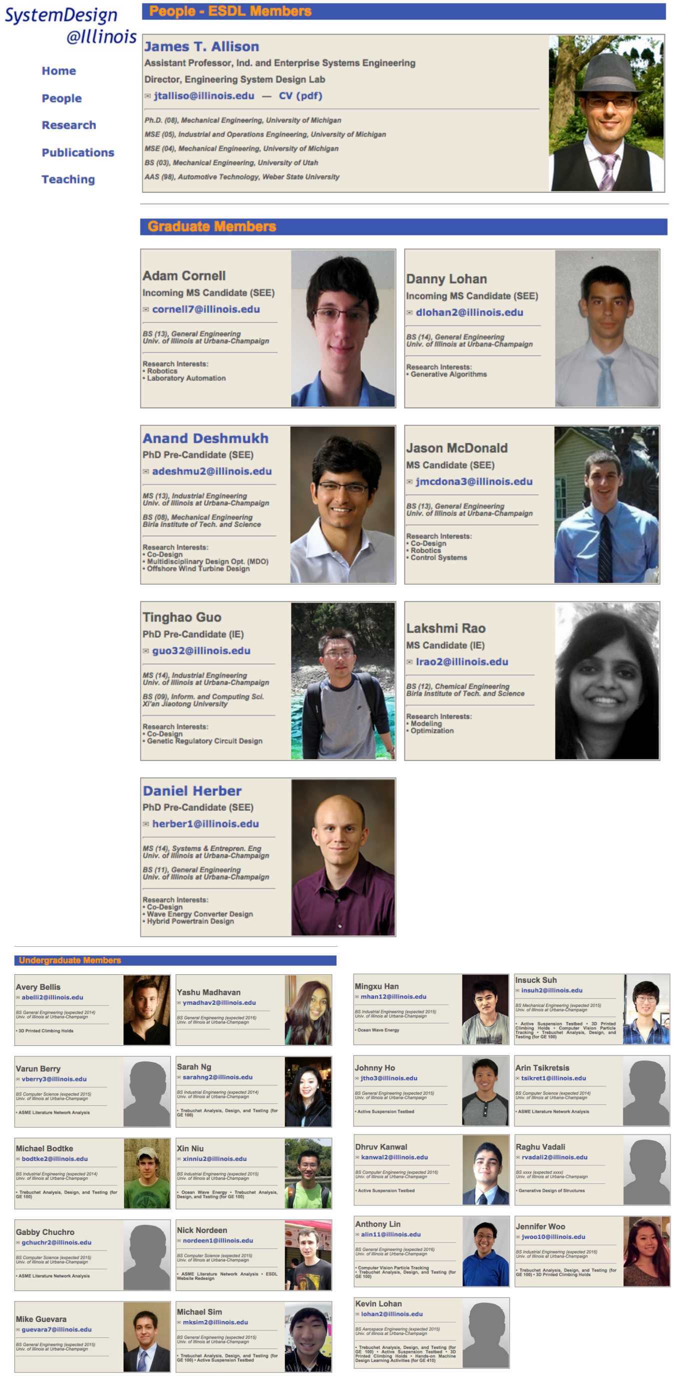


Engineering System Design Lab

We study and develop methods for solving challenging engineering design problems.

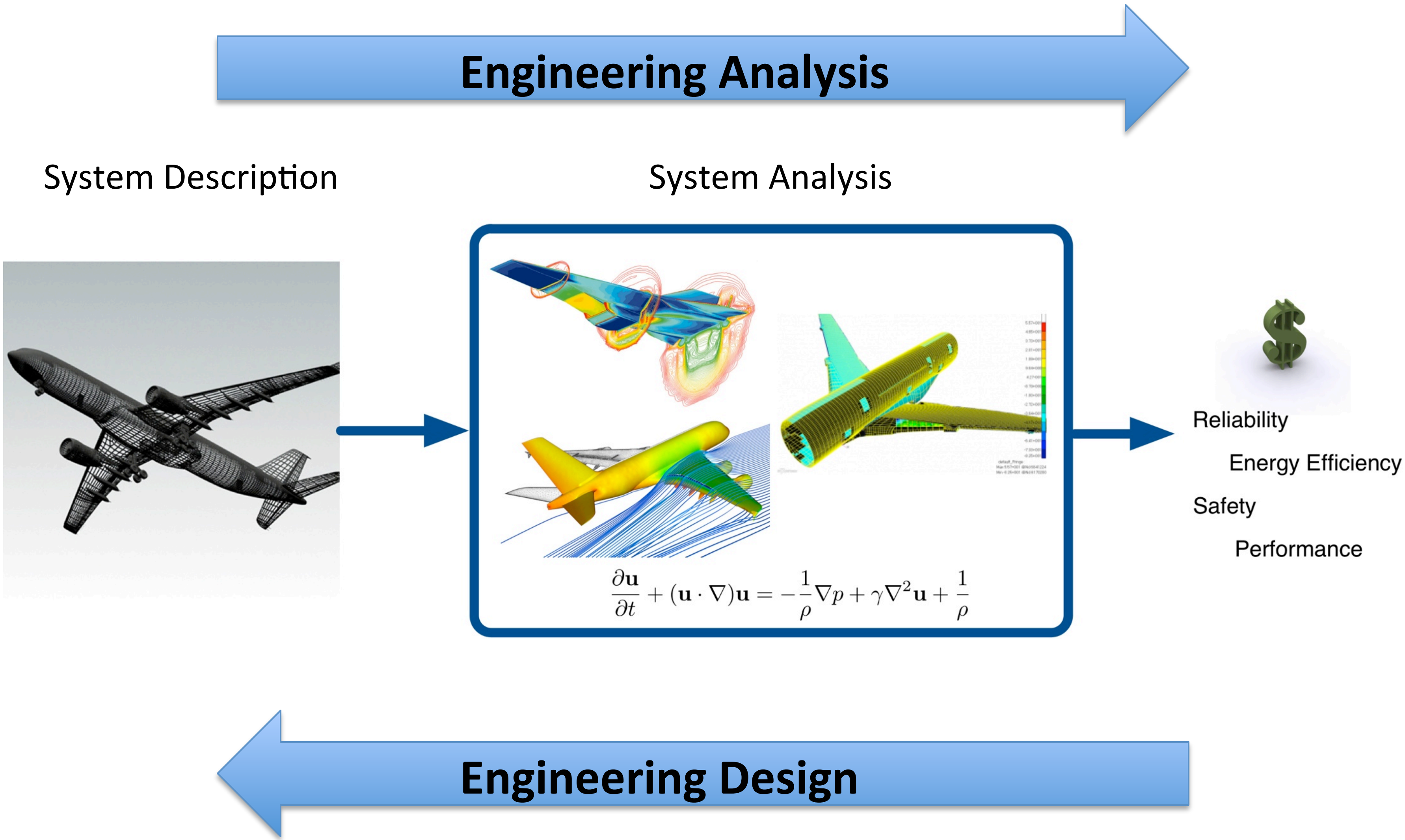
Thrust Areas:

- Multidisciplinary Dynamic System Design Optimization/Co-Design
- Direct Transcription (open-loop optimal control)
- Derivative Function Surrogate Modeling
- System Architecture Design
- Design of Reconfigurable Systems

Application Domains:

- Robotic system design
- **Wind and wave energy systems**
- Automotive design
- Spacecraft design
- Material and structural system design
- Synthetic biology

Engineering Design is the Inverse of Engineering Analysis

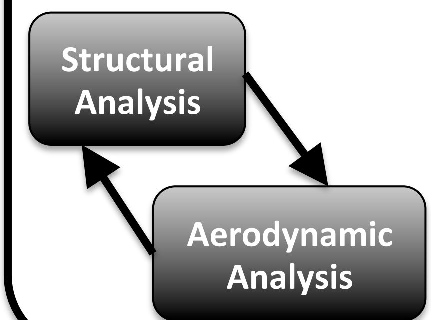


Integrated design methods address the interfaces between disciplines or system elements.

Analysis Coupling:

- Influence of component or discipline behavior/properties on another.
- Identifiable via analysis of physics models or sensitivity studies.
- Used often in systems engineering: integration models, multiphysics simulation
- **Overlook analysis coupling → inaccurate simulation**

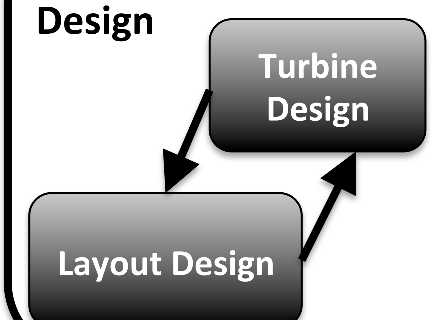
Example: Aeroelasticity



Design Coupling: $\frac{\partial x_{A*}}{\partial x_B}$

- The effect that changes in one design domain has on design decisions that **should** be made in another domain.
- Identified via model-based optimization studies.
- Design coupling is only starting to be addressed formally in systems engineering practice.
- **Overlook design coupling → suboptimal system design**

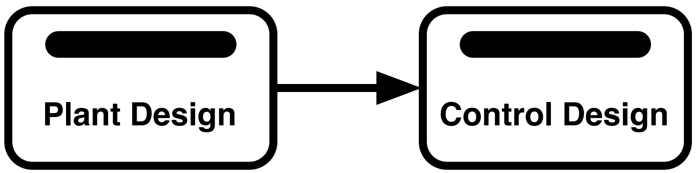
Example: Wind Plant Design



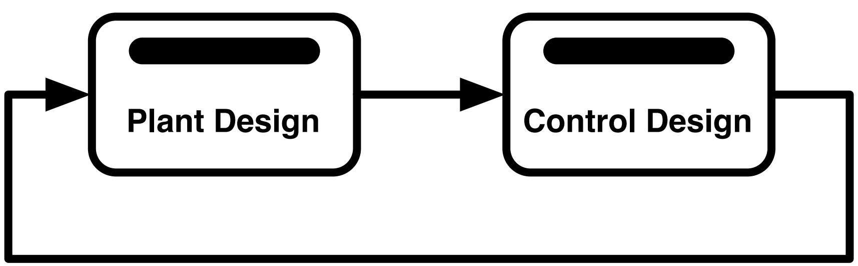
Design Process Options

(Physical + Control Design)

Conventional Sequential Design



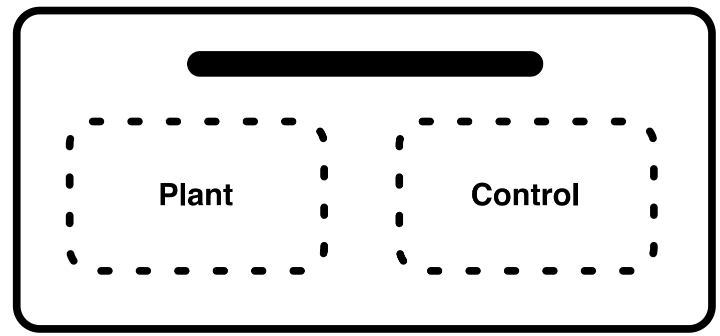
Iterated Sequential Design



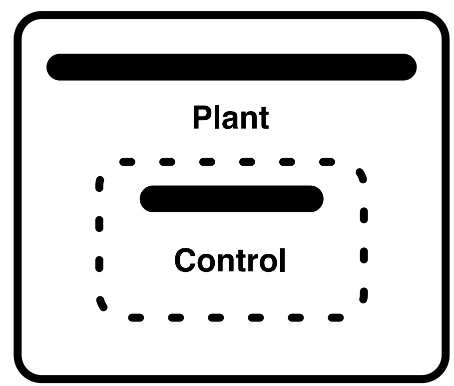
Co-Design

Integrated physical (plant) and control system design

Simultaneous Design



Nested Design



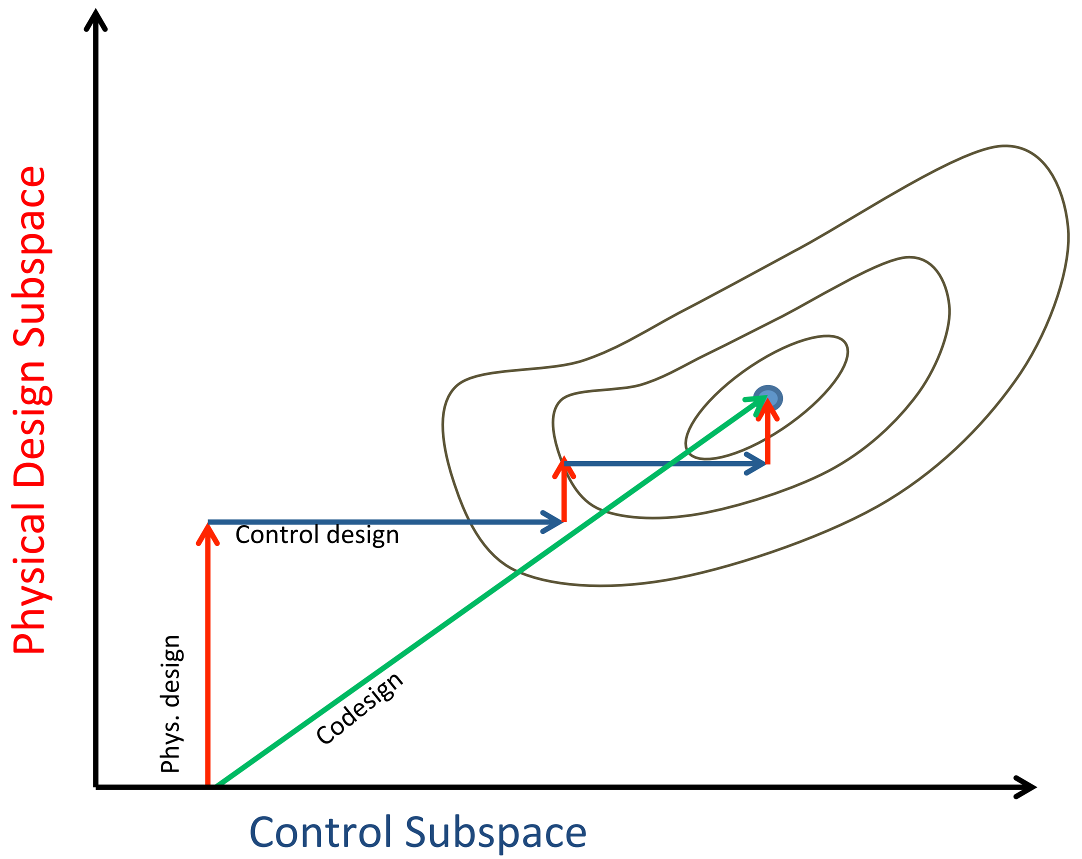
Distributed optimization is also an option

Co-Design: Integrated Physical and Control System Design

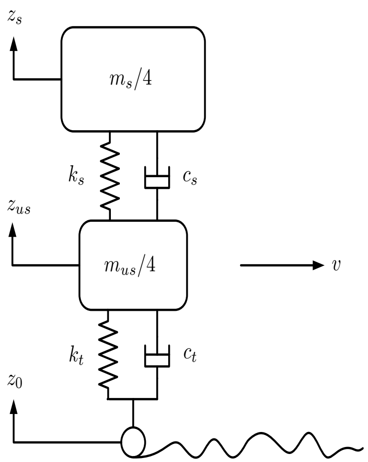
Navigate physical and control design subspaces simultaneously.

➔ System optimal designs

May be viewed as a specific class of Multidisciplinary Design Optimization (MDO) problems.

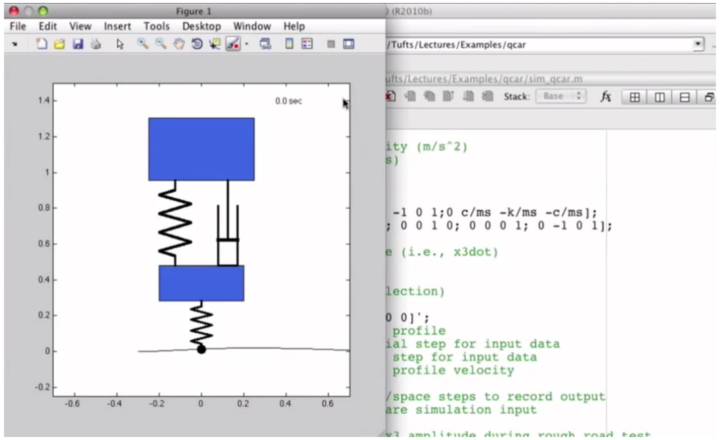


Co-design example: accounting for plant-control design coupling improves system performance.



Canonical co-design problem:

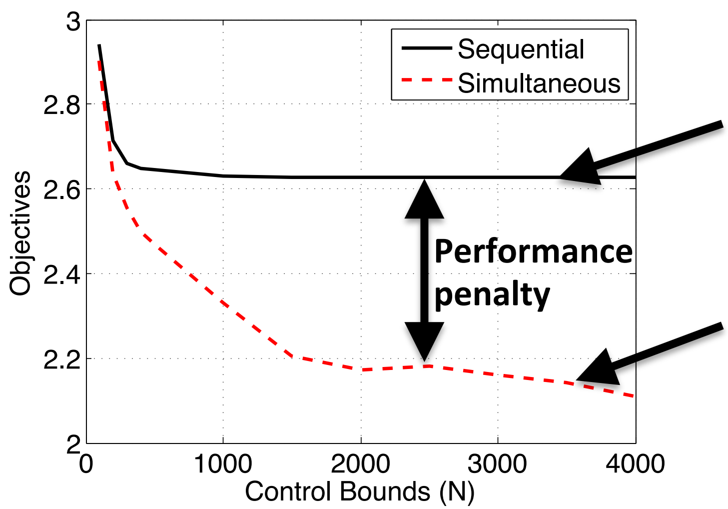
- Optimize comfort and handling of an **automotive suspension**
- Make decisions based on a quarter-car model
- Determine both physical and control system design



Allison, Guo, and Han (2014)

http://www.youtube.com/user/DesignImpact1

The performance gap between sequential and co-design results increases as active control plays a greater role in system operation.



Performance obtained using sequential design

Performance obtained using co-design

Design coupling between plant and control design is stronger for systems with greater control authority.

Wind turbine co-design accounts for coupling between structural and control system design.

$$AEP = 8760 \times \int_{v_i}^{v_o} P_m(v)\frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv$$

$$P_m = \frac{1}{2} C_p(\lambda, \beta)\rho\pi R^2 v^3$$

$$\max_{[\mathbf{x_p},\mathbf{x_c}]} \quad AEP$$

s.t.:

$A_g\mathbf{x_p} \leq \mathbf{0}$ ← **Linear constraints**

$\mathbf{g_p}(\boldsymbol{\xi}(t), \mathbf{x_p}) \leq \mathbf{0}$ ← **Deflection, stress, natural frequency constraints**

$\|\lambda(\Omega_r(t), v(t)) - \lambda_{opt}(\Omega_r(t), v(t))\| = 0$ ← **Maintains optimal power coefficient**

$\dot{\boldsymbol{\xi}}(t) = \mathbf{f}(\boldsymbol{\xi}(t), \mathbf{x_p}, \mathbf{u}(t))$ ← **System dynamics (FAST)**

$\mathbf{0} < \mathbf{x_l} \leq \mathbf{x_p} \leq \mathbf{x_u}$ ← **Bound constraints**

Control design variable: rotor speed controlled via generator torque

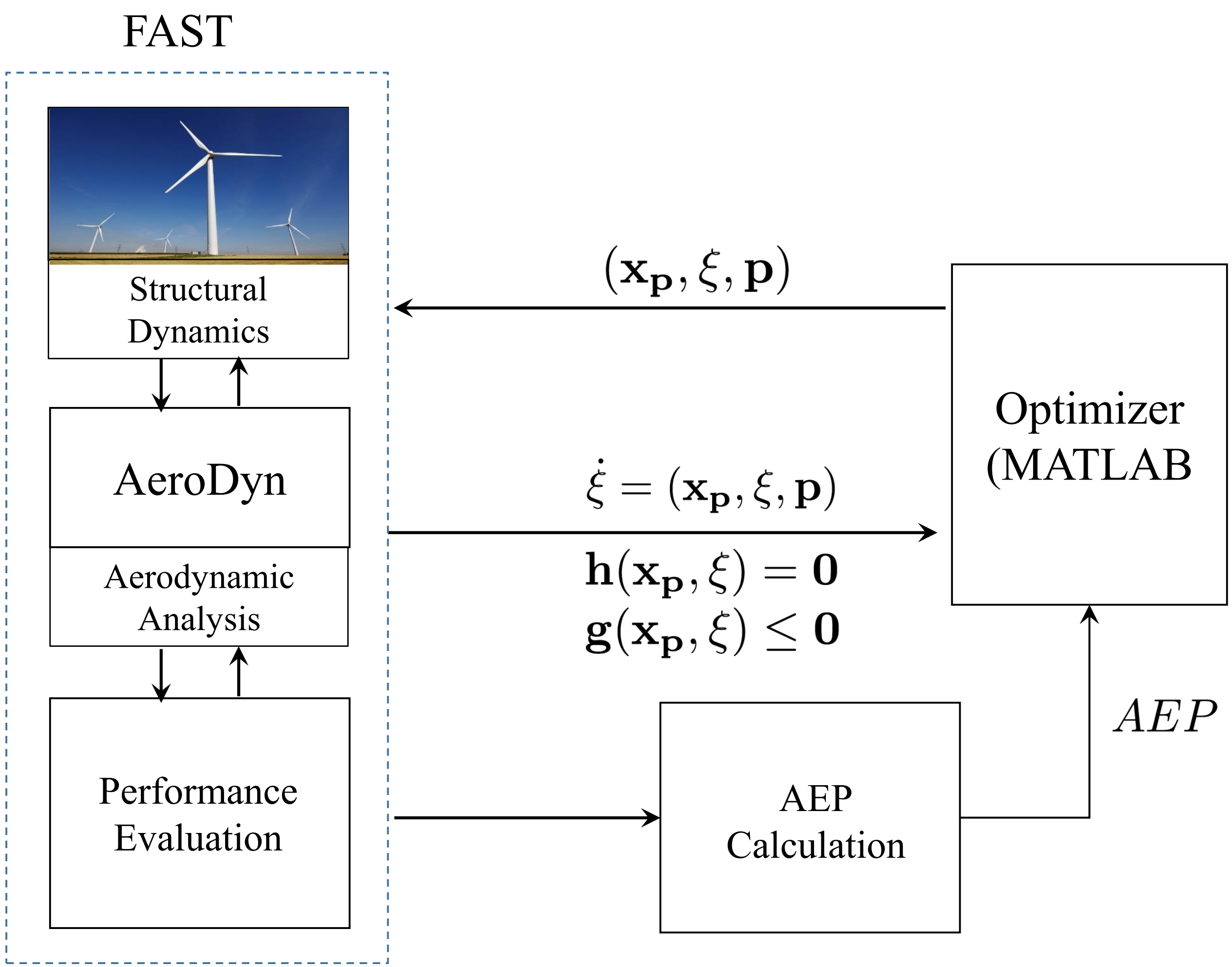
$$\mathbf{x_c} = \mathbf{u}(t) = \Gamma_g(t)$$

Plant design variables: blade pre-twist angles, chord spans, thickness, hub diameter, rotor diameter, and tower height

$$\mathbf{x_p} = [t_{w1},\ t_{w2},\ t_{w3},\ t_{w4},\ t_{w5},\ c_1,\ c_2,\ c_3,\ c_4,\ c_5,\ t_{h1},\ t_{h2},\ t_{h3}, D_h,\ D_r,\ H_t]^T$$

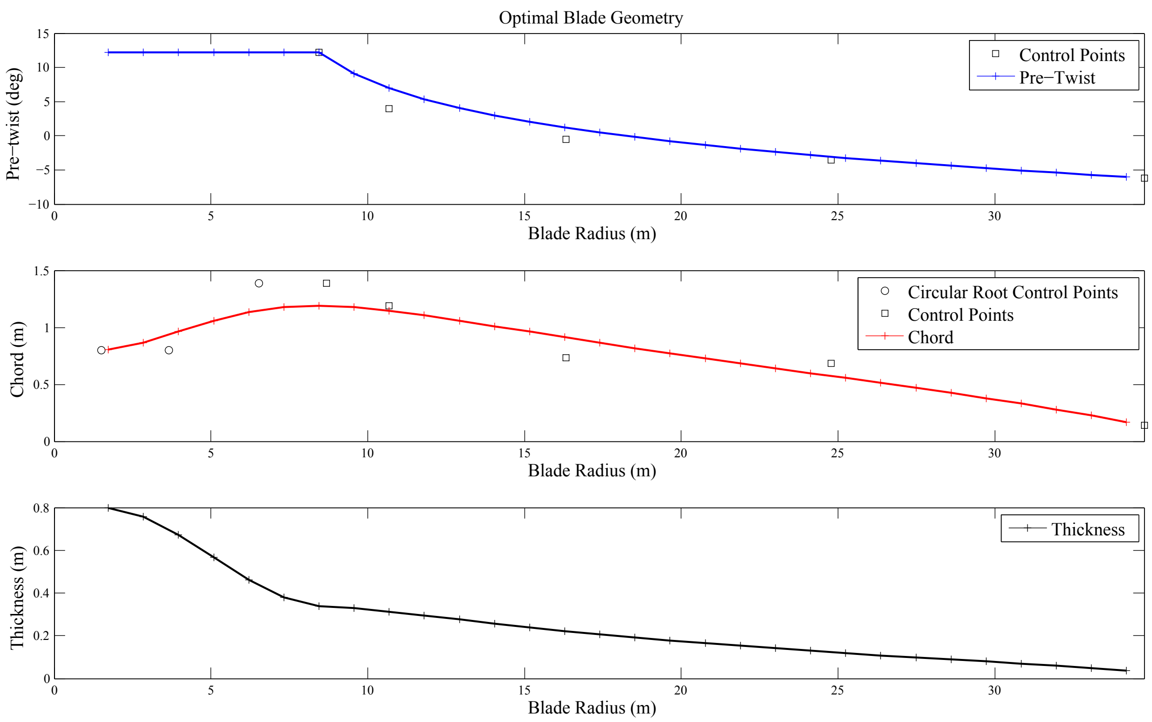
Wind-turbine co-design case studies investigated primarily by **Anand Deshmukh.**

Analysis workflow for wind turbine co-design problem.



HAWT co-design results show significant improvement over sequential design performance.

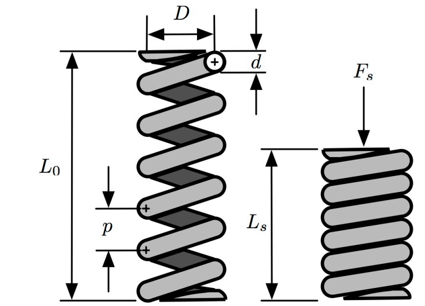
$\mathbf{x}_{\mathbf{p}*}$	Sequential	Nested	Simultaneous
D_h (m)	1.81	2.33	2.33
D_r (m)	68.58	69.51	69.51
H_t (m)	76.87	76.66	76.66
AEP (kW·h)	2996.9	3231.5	3231.5
% AEP Improvement	–	8.03	8.03



Balanced Co-Design

Many co-design studies utilize simplified plant models

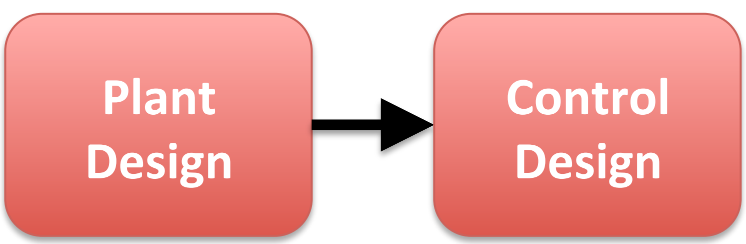
- e.g., intermediate variables are treated as independent design variables
- Model parameters usually should not be treated as independent design variables.



$$k_s = \frac{d^4 G}{8 D^3 N_a \left(1 + \frac{1}{2C^2}\right)}$$

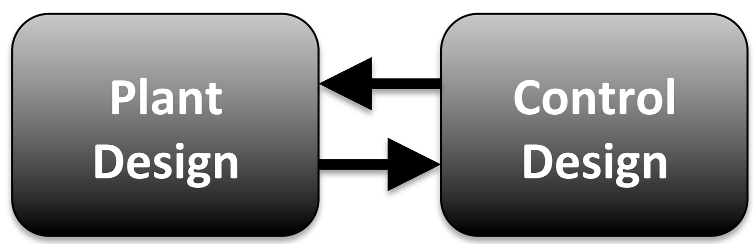
Consequences:

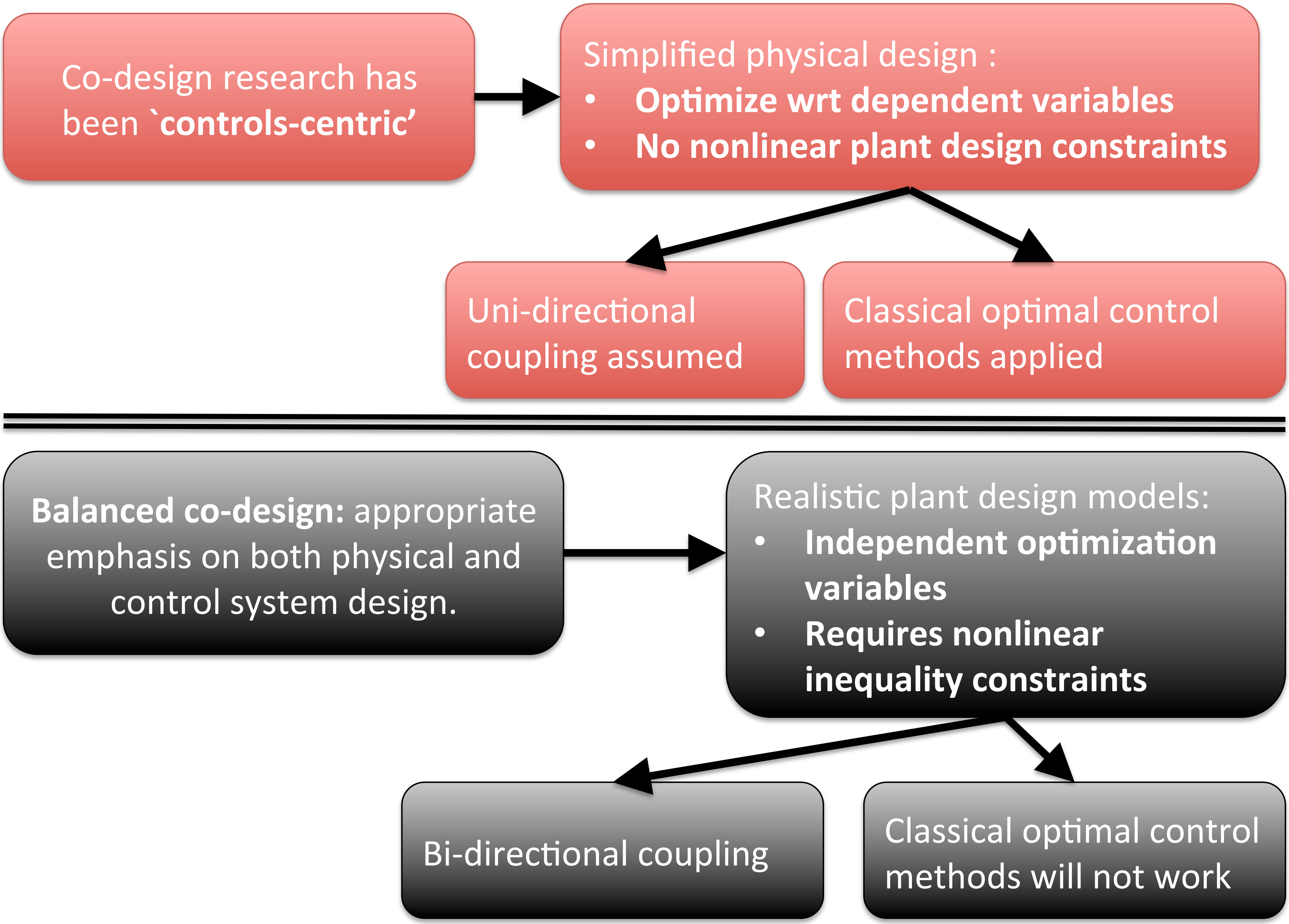
Constraints on independent $\boldsymbol{x_p}$ are overlooked, and co-design problems seem to have **unidirectional** coupling.



Reality:

Most co-design problems have **bidirectional** coupling (e.g., fatigue and other constraints depend on state trajectories, which depend on $\mathbf{x_c}$)




Co-design research has been `controls-centric'
Simplified physical design :
• Optimize wrt dependent variables
• No nonlinear plant design constraints
Uni-directional coupling assumed
Classical optimal control methods applied
Balanced co-design: appropriate emphasis on both physical and control system design.
Realistic plant design models:
• Independent optimization variables
• Requires nonlinear inequality constraints
Bi-directional coupling
Classical optimal control methods will not work

Advancements in Balanced Co-Design

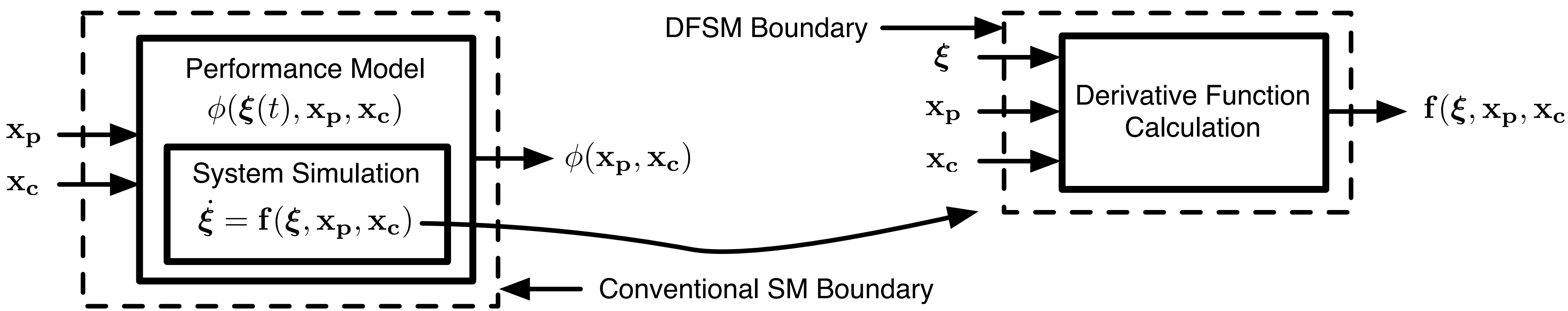
Direct optimal control methods:

- Support balanced co-design formulations, including general inequality constraints on physical system design (stress, deflection, fatigue, etc.)
- Simultaneous optimization with respect to both plant and control design variables
- Numerically efficient

Co-design with high-fidelity multidisciplinary models:

- Challenging to incorporate computationally expensive models with optimization-based co-design
- Important for navigating design interactions at early design stages
- Need to enable co-design with high-fidelity models to account for new elements of design coupling
- **DFSM:** novel surrogate modeling method that capitalizes on the nature of dynamic systems to reduce computational expense

Derivative function surrogate modeling: enable co-design with high-fidelity computational models

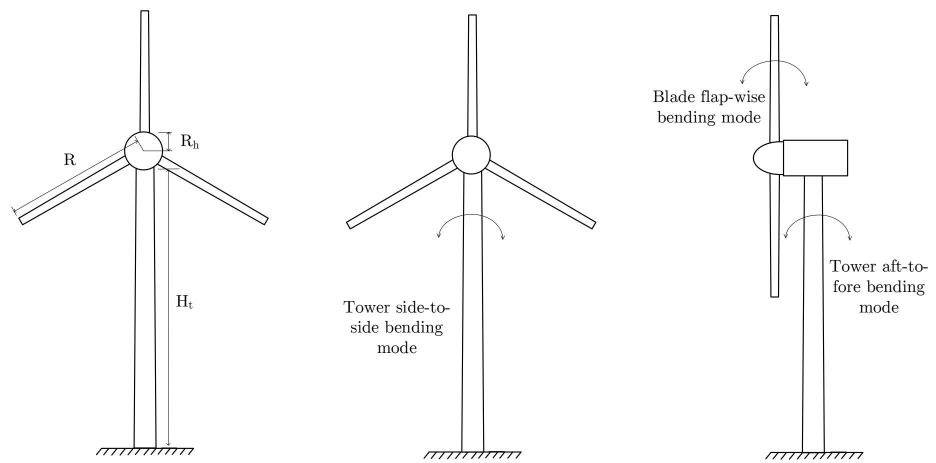


DFSM reduces overall system optimization expense significantly

- Initial case study: order of magnitude expense reduction
- Significant potential for enabling optimization based on high-fidelity models that account for more interactions

DFSM produces dramatic savings in computational expense:

Wind turbine co-design with moderate-fidelity dynamic model



	DT using $\mathbf{f}(\cdot)$	DFSM using $\hat{\mathbf{f}}(\cdot)$	SM using $\hat{\phi}(\cdot)$
No. $\mathbf{f}(\cdot)$ evaluations	25160	2800	N/A
Solution time	419 min	124 min	618 min
FAST evaluation time	50.9%	18.8%	87.1%

Anand Deshmukh, James T. Allison. 'Design of Nonlinear Dynamic Systems using Surrogate Models of Derivative Functions.' In the Proceedings of the 2013 ASME Design Engineering Technical Conference, DETC2013-12262. ASME, Aug. 4–Aug. 7.

Anand P. Deshmukh, James T. Allison. 'Simultaneous Structural and Control System Design for Horizontal Axis Wind Turbines.' In the Proceedings of the 9th AIAA Multidisciplinary Design Optimization Specialist Conference. AIAA, Apr. 8–11 2013.

Anand P. Deshmukh, James T. Allison. 'Multidisciplinary Dynamic Optimization of Horizontal Axis Wind Turbine Design.' Structural and Multidisciplinary Optimization, In review.

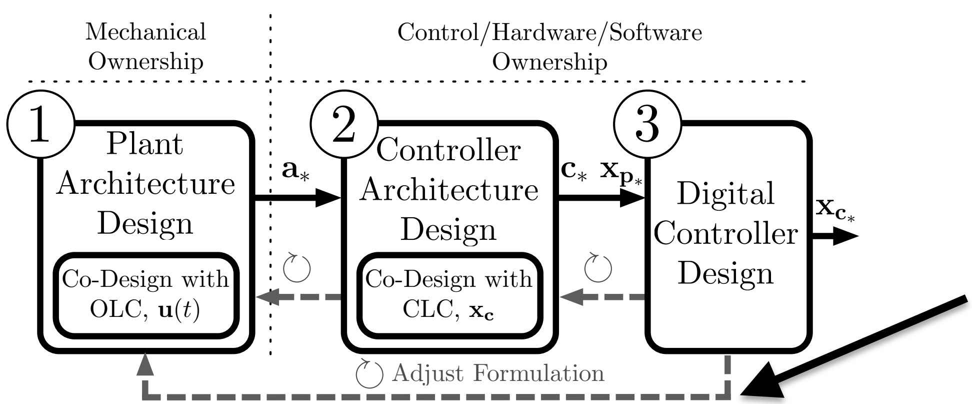
Utilizing Co-Design in Systems Engineering

Significant potential for

- Enhancing **design integration**
- Improving system performance, capitalize on **passive dynamics** in an active system
- Tailor structural/mechanical/control system designs → **system optimality**
- Identifying problems due to interactions early

How might co-design be used within systems engineering?

- Especially appropriate for **early-stage design** (predesign)
- Identify qualitative synergy mechanisms that can guide later design efforts
- Tool for mechanical/structural designers to develop a design they are confident has accounted for coupling with control system design



Adjust co-design formulation if we discover something that was overlooked

Deshmukh, Herber, and Allison (2015)

Future of Co-Design in Wind Energy Systems Engineering

- Balanced co-design is an extensible framework (easily add new considerations)
- Development of reliable, flexible, accurate models that are appropriate for co-design is a significant challenge
- Improve ability to solve co-design problems with increasing levels of analysis fidelity
- Use co-design concepts to help enhance design integration in the wider systems engineering process
- Move toward solving Systems-of-Systems (SoS) problems, such as more comprehensive farm- (plant-) level co-design, grid integration
- Use distributed optimization to support problem-specific optimization algorithms
- Utilize systematic co-design studies to reveal more general design principles and synergy mechanisms for wind energy systems