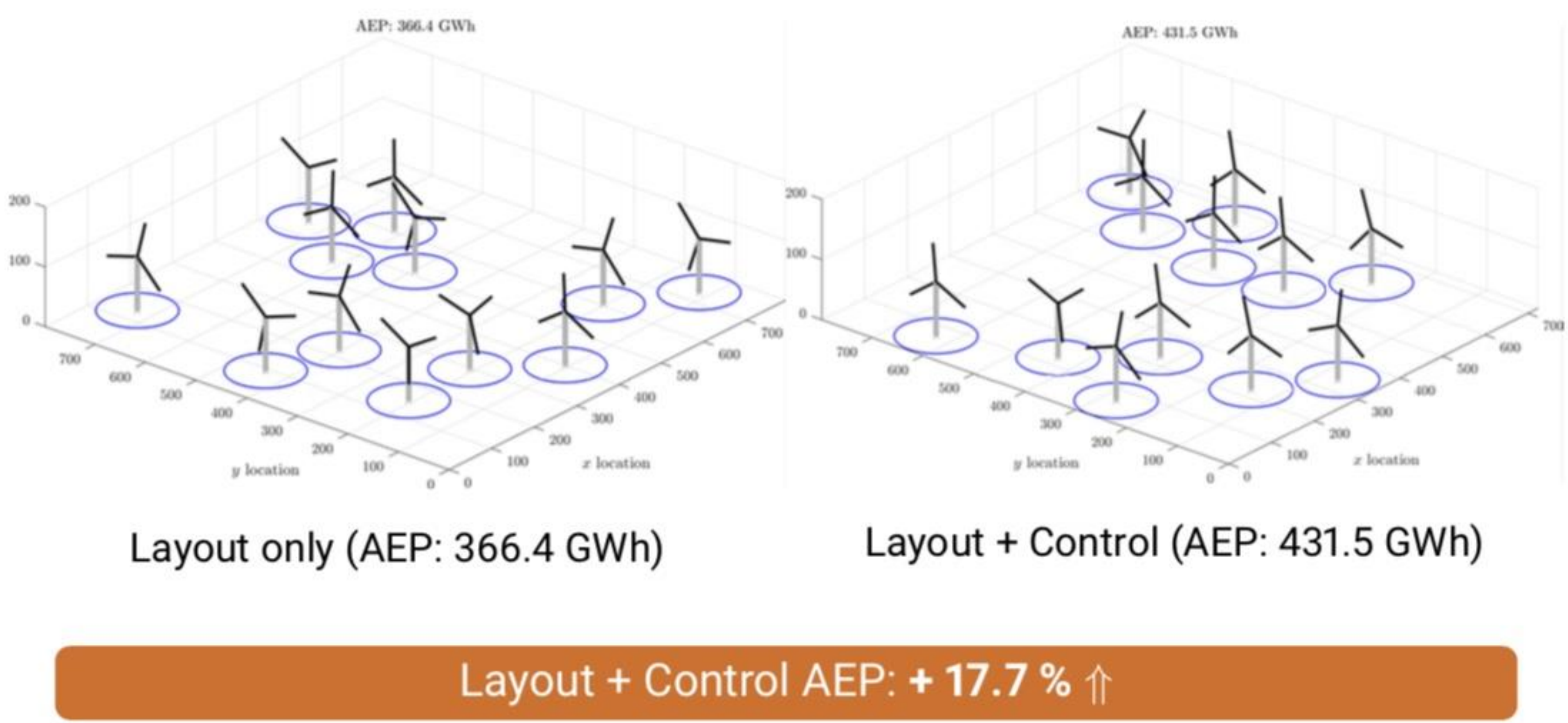
Integrated Physical and Control System Design: A Strategy for New Performance Levels in Renewable Energy Systems

Prof. James T. Allison
Engineering System Design Laboratory
University of Illinois at Urbana-Champaign
www.systemdesign.illinois.edu

Why integrated design methods?

Why integrated design methods?

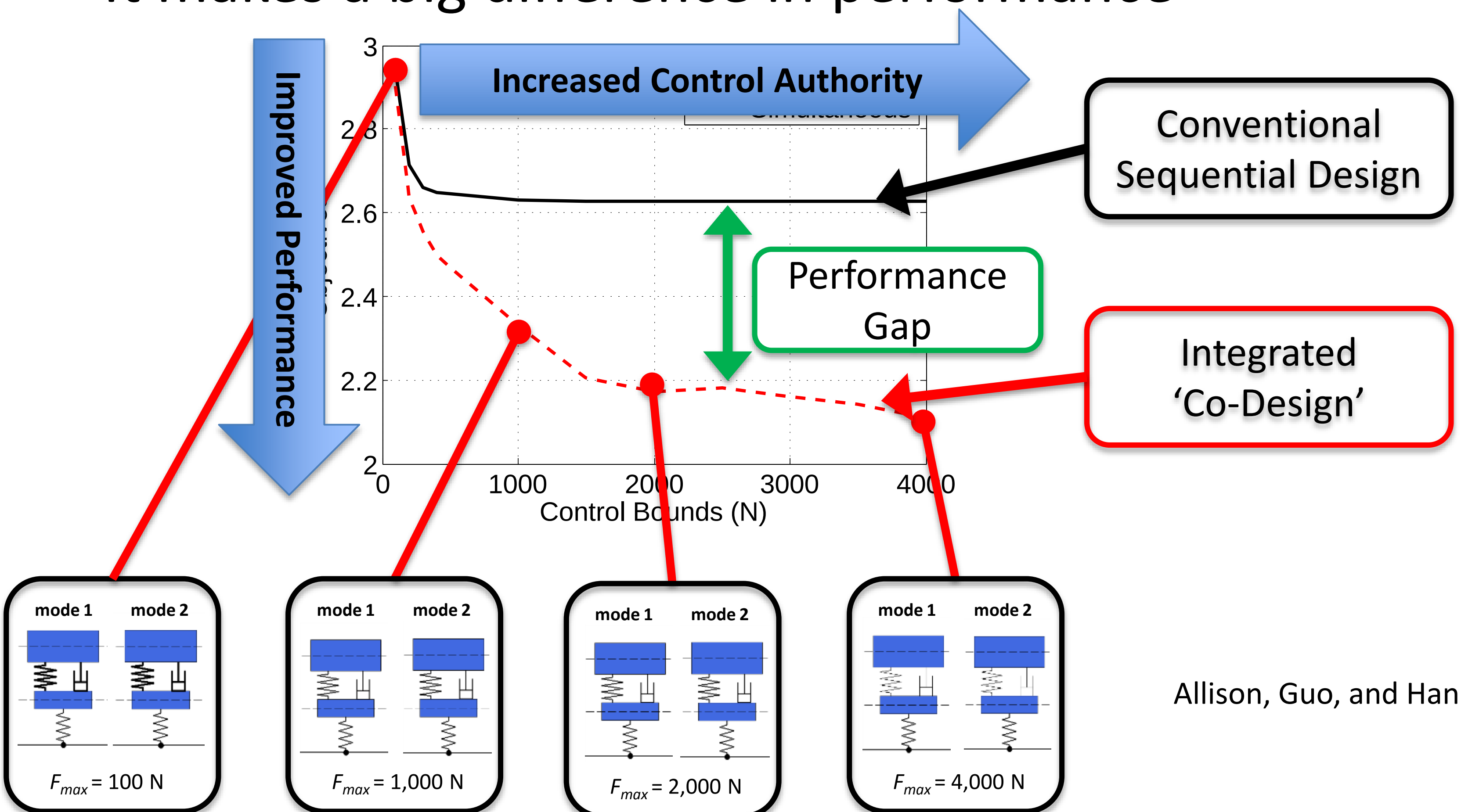
- It makes a big difference in performance



Deshmukh and Allison (2017)

Why integrated design methods?

- It makes a big difference in performance

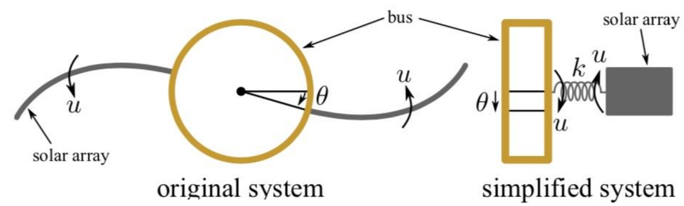


Allison, Guo, and Han (2013)

Why integrated design methods?

- It makes a big difference in performance
- Helps engineers identify ultimate performance limits (e.g., fair technology evaluation)
- New design insights for unprecedented systems

Example: design rules identified via non-dimensional co-design study of strain-actuated solar array attitude control system – Herber and Allison (2017)



$$\min_{k,\bar{u}(\bar{t})} \; -\frac{u_{\max} t_f^2}{4\pi^2 J}\bar{\theta}(2\pi)$$

subject to:

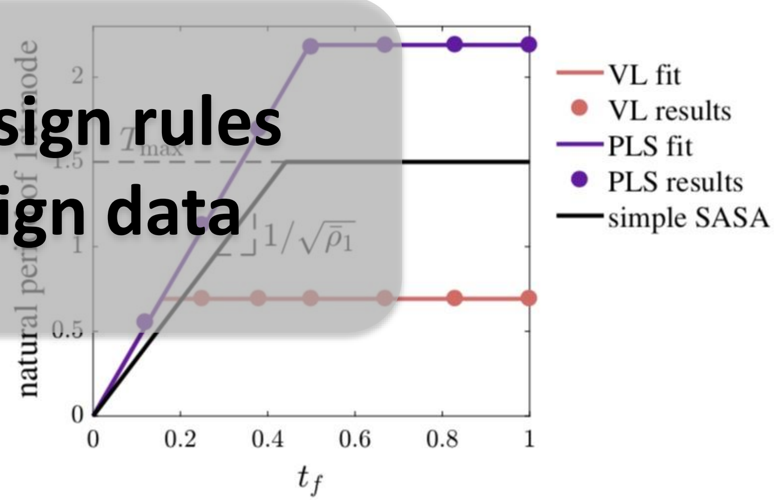
$$\bar{\theta}'' = -\frac{k t_f^2}{4\pi^2 J} \ldots$$

$$\bar{\theta}(0) = \bar{\theta}'(0) = 0$$

$$\bar{\theta}'(2\pi) = 0$$

$$|\bar{u}(\bar{t})| \leq 1$$

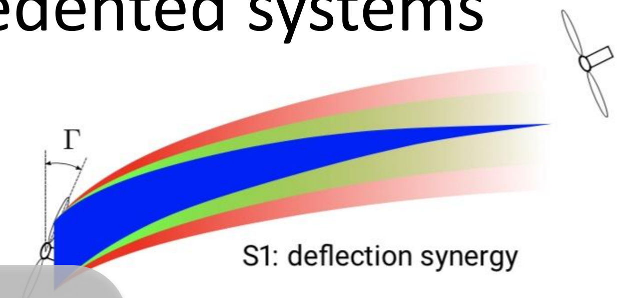
Extract design rules from design data



Why integrated design methods?

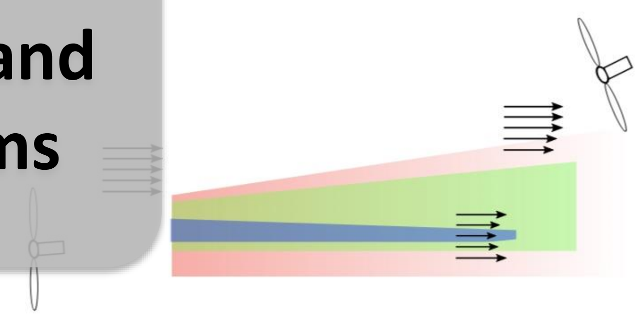
- It makes a big difference in performance
- Helps engineers identify ultimate performance limits (e.g., fair technology evaluation)
- New design insights for unprecedented systems

Example: identify ***synergy mechanisms*** through systematic numerical studies – Allison, Herber, and Deshmukh (2015), Deshmukh and Allison (2017)



A specific underlying design mechanism that facilitates overall system performance improvements when two or more design elements are varied synergistically.

Reveal and understand synergy mechanisms



S2: expansion and propagation synergy

Engineers can use the resulting intuition to pursue increased system performance.

What are integrated active system design (co-design) methods?

What are integrated active system design (co-design) methods?

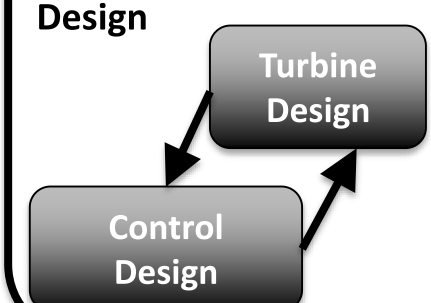
- Different from design for controllability
- Beyond control design based on detailed plant models
- Simultaneous consideration of both plant and control design decisions
- Understanding and full use of ***design coupling*** between physical and control design decisions

Design Coupling:

Exists if changing one element of a system design impacts how another system element ***should*** be designed

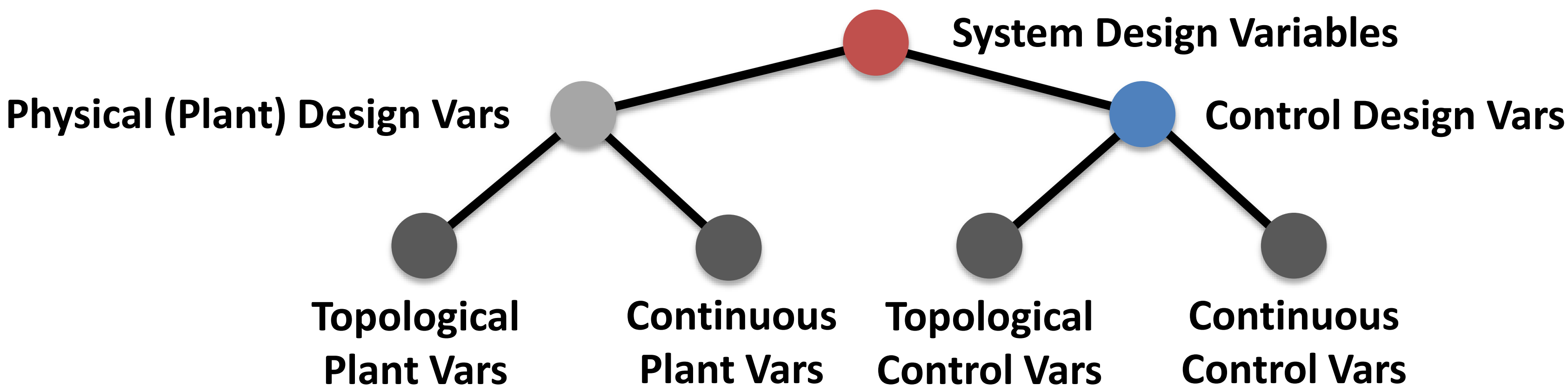
Strong design coupling → integrated design methods make a big difference in system performance

Example: Wind Turbine Design



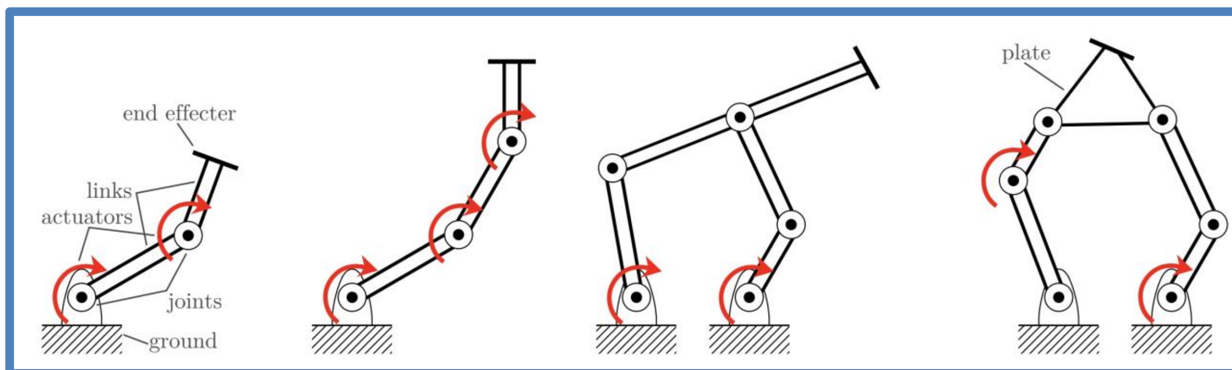
Co-design problem properties

Simultaneous consideration of multiple sets of design decision variables:



Example: robotic manipulator design

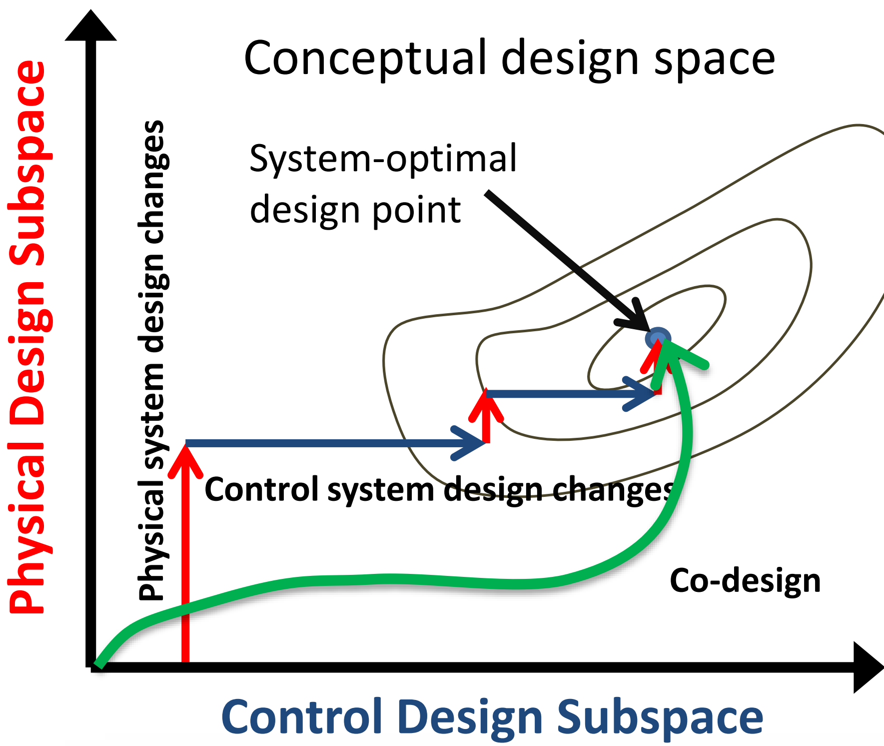
(Herber 2017)



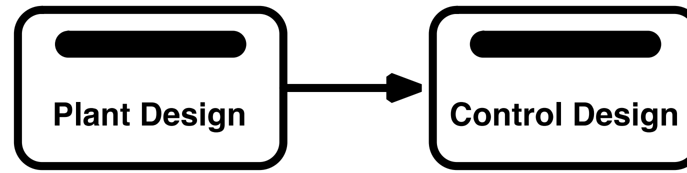
Design decisions: #/arrangement of links, link geometry, joint types, sensors/actuators, control architecture/laws)

Aim for fully-integrated design: physics, design, subsystem interactions

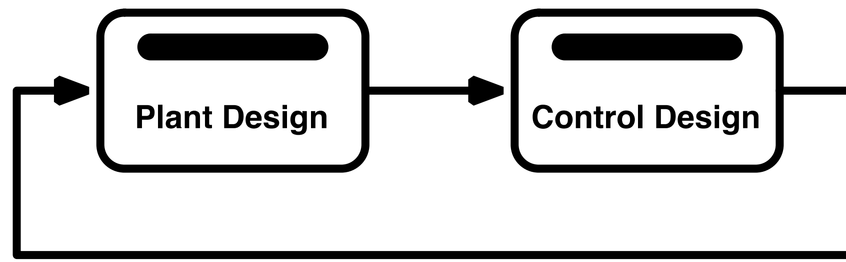
Design process options:



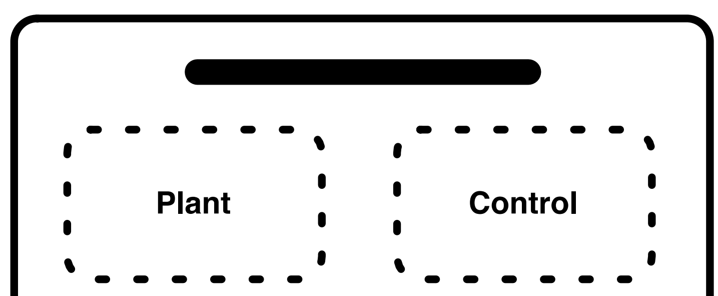
Conventional Sequential Design



Iterated Sequential Design



Simultaneous Co-Design



Simultaneous Co-Design Problem Formulation:

$$\min_{\boldsymbol{x}_p,\boldsymbol{x}_c} \quad \Psi = \int_{t_0}^{t_f} \mathcal{L}\left(t,\boldsymbol{\xi},\boldsymbol{x}_c,\boldsymbol{x}_p\right) dt \; + \mathcal{M}\left(\boldsymbol{\xi}(t_0),\boldsymbol{\xi}(t_f),\boldsymbol{x}_c,\boldsymbol{x}_p\right)$$

$$\text{s.t.} \quad \dot{\boldsymbol{\xi}} - \boldsymbol{f}\left(t,\boldsymbol{\xi},\boldsymbol{x}_c,\boldsymbol{x}_p\right) = \boldsymbol{0}$$

$$\boldsymbol{C}\left(t,\boldsymbol{\xi},\boldsymbol{x}_c,\boldsymbol{x}_p\right) \leq \boldsymbol{0}$$

$$\boldsymbol{\phi}\left(\boldsymbol{\xi}(t_0),\boldsymbol{\xi}(t_f),\boldsymbol{x}_c,\boldsymbol{x}_p\right) \leq \boldsymbol{0}$$

Apply the same system objective function consistently across both design domains

Current state-of-the-art in co-design

Current state-of-the-art in co-design

Building upon earlier related work:

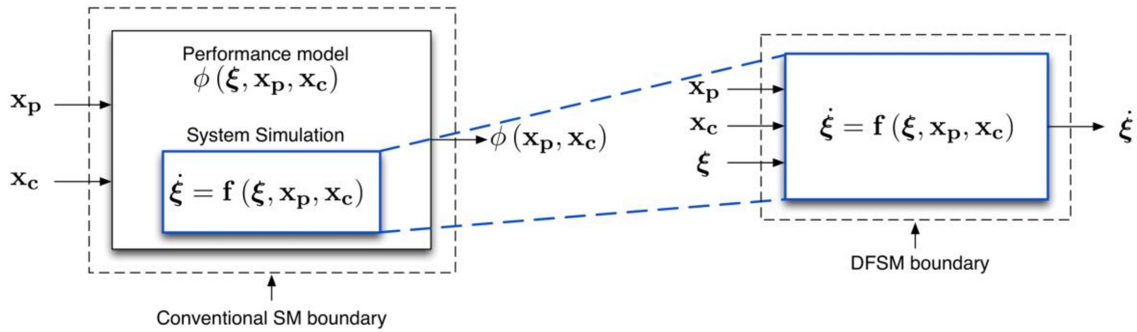
- **Control-Structure Interaction (1980s-1990s)**
- **Multidisciplinary Design Optimization (1990s-present)**
- **Initial Co-Design Theory and Methods (early 2000's)**

Previous gaps addressed to produce present significant capabilities:

- **More general/ comprehensive problem solution**
- **Efficient solution using high-fidelity simulations**

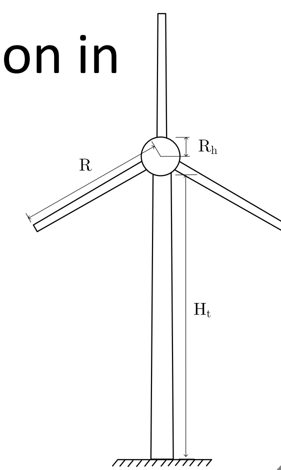
Example method for high-fidelity co-design problems:

- Derivative Function Surrogate Modeling
- Capitalize on structure of dynamic system design problems to enable use of accurate simulations



HAWT Co-Design: order of magnitude reduction in computational expense

	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 P Deshmukh, James T Allison. *'Design of Dynamic Systems using Surrogate Models of Derivative Functions.'* ASME Journal of Mechanical Design, 139(10), p. 101402-101402-12, Aug 2017.

Current state-of-the-art in co-design

Building upon earlier related work:

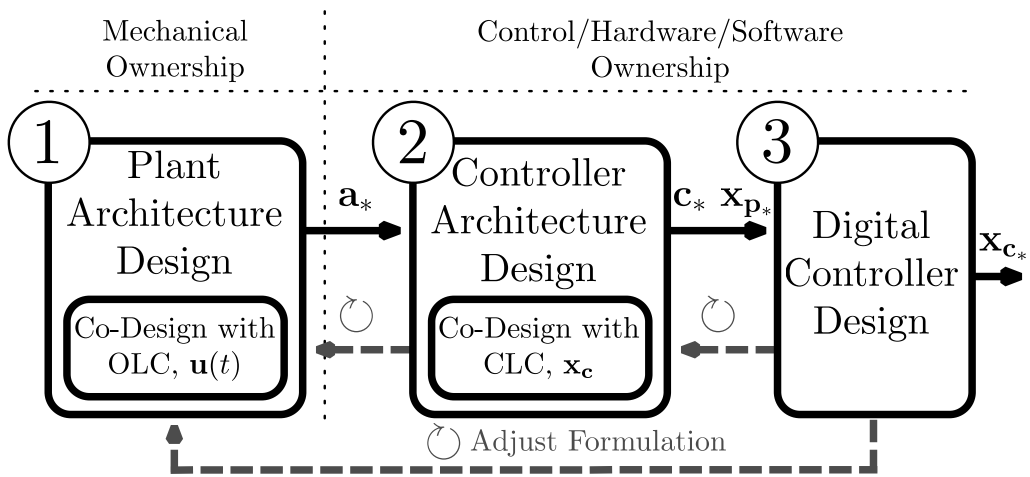
- Control-Structure Interaction (1980s-1990s)
- Multidisciplinary Design Optimization (1990s-present)
- Initial Co-Design Theory and Methods (early 2000's)

Previous gaps addressed to produce present significant capabilities:

- More general/ comprehensive problem solution
- Efficient solution using high-fidelity simulations
- Bridging the gap to systems engineering practice

Bridging the gap to systems engineering practice:

Concept: Use co-design for early-stage plant development, inform reformulation at later stages



Deshmukh, Herber, and Allison (2015)

Infusing co-design with experimental data
(Chris Vermillion, NC State)

What else? What impedes adoption in practice?

Current state-of-the-art in co-design

Building upon earlier related work:

- Control-Structure Interaction (1980s-1990s)
- Multidisciplinary Design Optimization (1990s-present)
- Initial Co-Design Theory and Methods (early 2000's)

Previous gaps addressed to produce present significant capabilities:

- More general/ comprehensive problem solution
- Efficient solution using high-fidelity simulations
- Bridging the gap to systems engineering practice

What are we missing? What work is left to be done?

- Not yet adopted widely in industry (even when design coupling is strong)

Current state-of-the-art in co-design

Building upon earlier related work:

Control-St
Inter
(1980

Initial Co-Design
nd Methods
2000's)

Previous
capabilities:

More
compr
problen

the gap to
ngineering
ctice

Why?

- **Technical limitations?**
- **Not enough potential value?**
  (design coupling, market impact)
- **Organizational challenges?**
- **Perception/psychology?**

What are we missing? What work is left to be done?

Not yet adopted widely in industry (even when design coupling is strong)

Current state-of-the-art in co-design

Building upon earlier related work:

Control-Structure Interaction (1980s-1990s)	Multidisciplinary Design Optimization (1990s-present)	Initial Co-Design Theory and Methods (early 2000's)

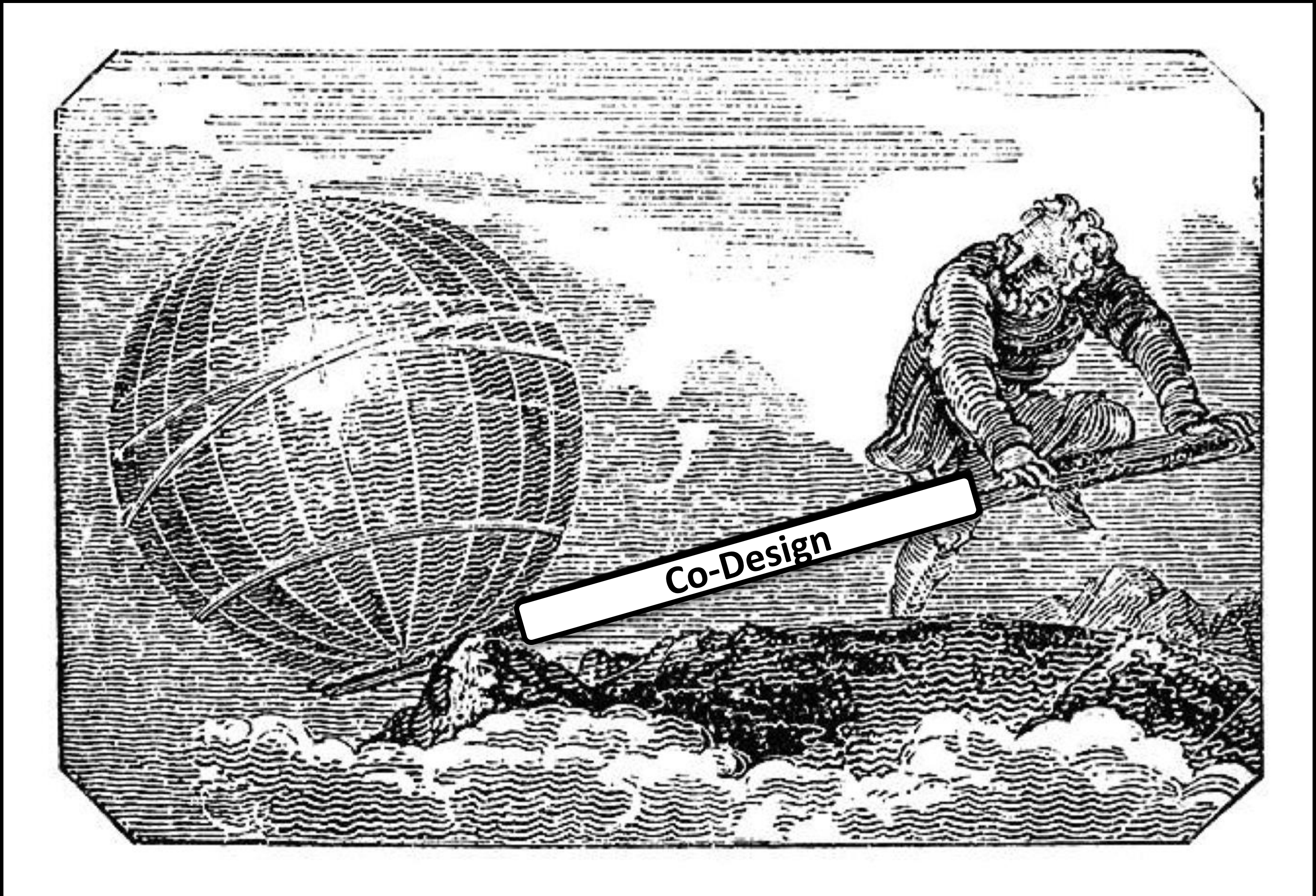
Previous gaps addressed to produce present significant capabilities:

More general/ comprehensive problem solution	Efficient solution using high-fidelity simulations	Bridging the gap to systems engineering practice

What are we missing? What work is left to be done?

Not yet adopted widely in industry (even when design coupling is strong)	No existing demonstration of co-design using a large-scale engineering system

Vision for Co-Design of Renewable Energy Systems



Vision for Co-Design of Renewable Energy Systems

Strong present technical capabilities in co-design

- Solution of highly-integrated, comprehensive co-design problems using high-fidelity simulations (including architecture decisions)

Renewable energy systems have strong design coupling

- Performance gains available, rich design interactions

Industry adoption is limited – what is missing?

- Convincing demonstration? Alignment with existing design organizations/processes?

ARPA-E: Pivotal opportunity for co-design

- Translate co-design principles and methods into real systems
- **Doable:** strong design coupling, capable methods, high-impact application
- **Strategic collaborations:** discover what advances are needed at interfaces (realize next level of co-design capability)