Control Co-Design: Achieving New Functionality and Performance Via Integrated Physical and Control System Design

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What is Control Co-Design (CCD)?

Historical CCD Development

Current CCD State-of-the-Art

CCD Impact and Open Questions

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Historical CCD Development

Current CCD State-of-the-Art

CCD Impact and Open Questions

What is Control Co-Design?

Class of integrated engineering system design methods that:

- Consider the explicit relationship between **physical** and **control system** design decisions
- Answer the question:

"How should the physical aspects of an actively controlled engineering system be designed such that passive and active properties interact synergistically for system-optimal performance?"

- Account explicitly for both ***physics coupling*** and ***design coupling***
- Support discovery of ***non-obvious*** physical and control system design solutions that enable new levels of performance and functionality
- When based on design optimization, are a subset of ***Multidisciplinary Design Optimization*** (MDO) methods where at least one discipline is control system design

James T Allison, Daniel R Herber. 'Multidisciplinary Design Optimization of Dynamic Engineering Systems.' AIAA Journal, 52(4), pp. 691-710, Apr 2014. DOI: 10.2514/1.J052182

Design Optimization Across Multiple Sets of Disciplinary Design Decisions

Consider a general bi-discipline optimization problem with two sets of disciplinary design variables: *x* and *y*

- System optimality requires simultaneous optimization of *x* and *y*
- Sequential design does not produce system-optimal designs if cross terms exist
- Several formulations are mathematically equivalent to simultaneous design

Simultaneous optimization formulation

$$\begin{aligned} \min_{x,y} \quad & f_x(x) + f_y(y) + f_{xy}(x,y) \\ \text{subject to:} \quad & g_x(x) \leq 0,\ g_y(y) \leq 0 \\ & g_{xy}(x,y) \leq 0 \end{aligned}$$

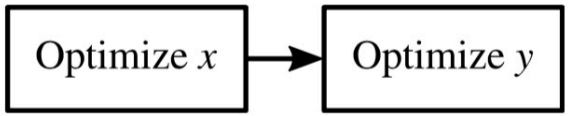


Figure: Sequential design.

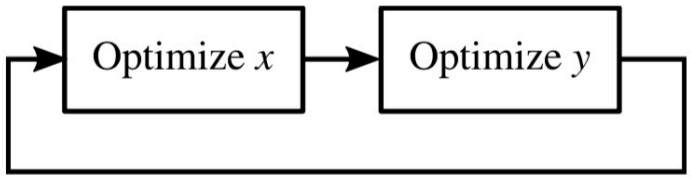


Figure: Iterated sequential design.

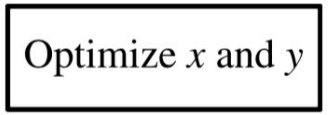


Figure: Simultaneous design.

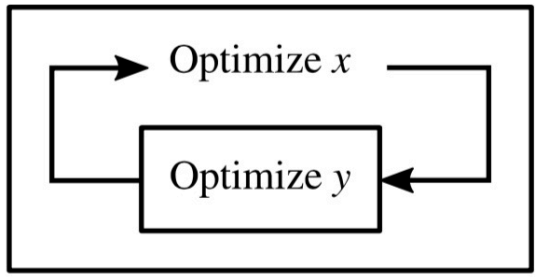
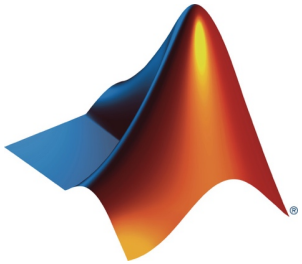


Figure: Nested design.

In practice, how are active systems designed?

Largely sequential processes:



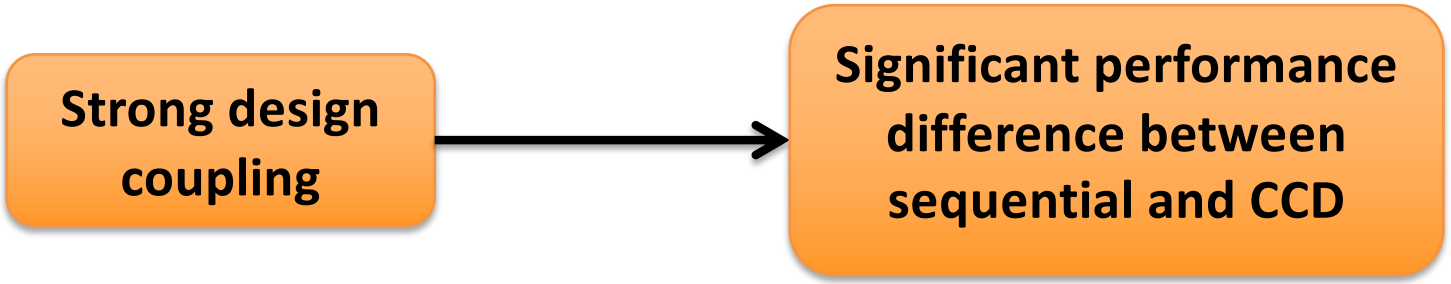
Common refrain from control system engineers:

"If only I could change X about the plant (physical system), the system would perform so much better."

- But does the control engineer have a full understanding of the coupling between plant and control design? Should plant design be guided by more than expert intuition?

What difference can CCD make? Is it worth the investment?

Typically:



What exactly is design coupling?

If we make changes in one design domain, does that influence how we ***should*** make decisions in other domains?

- If $\Delta \boldsymbol{x}_p \rightarrow$ large changes in optimal $\boldsymbol{x}_c$, design coupling is strong
- Often physics coupling gives rise to design coupling
- Systems with **rich passive dynamics**, such as flexible structures or nonlinear elements, often have strong design coupling
- Plant-control design coupling is **bi-directional**
- Design coupling will be defined more explicitly shortly

CCD impact example: robotic manipulator design

- Defined pick-and-place task
- Optimization of link geometry, counter masses, and torque trajectories
- Constraints on: stress, deflection, max torque, start and end velocities

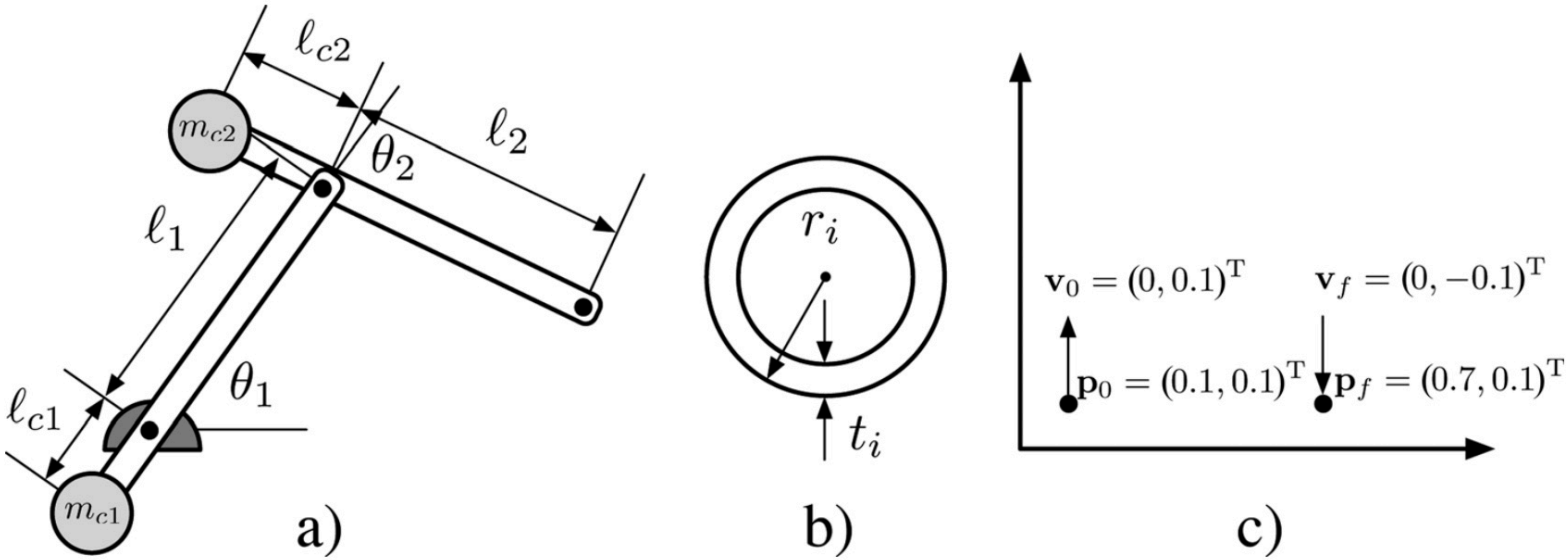


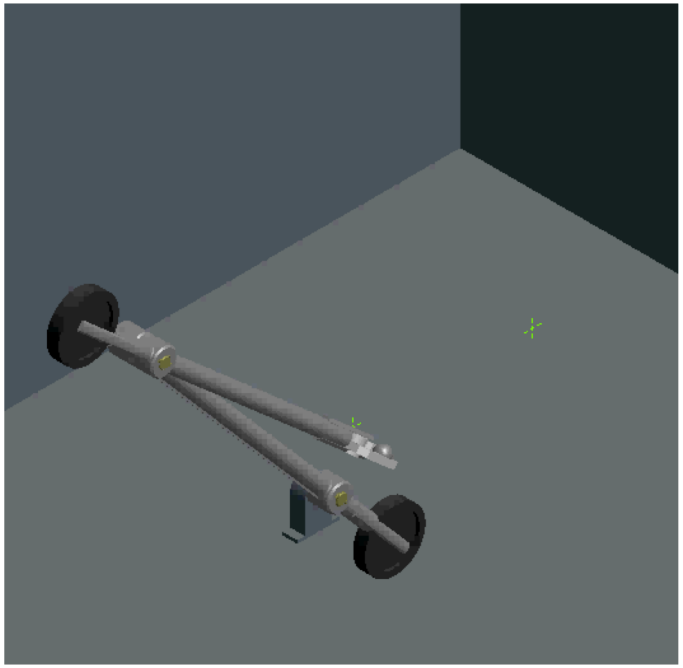
Fig. 1 (*a*) Counterbalanced two-link planar manipulator, (*b*) section view of link *i*, and (*c*) task A initial and final conditions

James T Allison. 'Plant-Limited Co-design of an Energy-Efficient Counterbalanced Robotic Manipulator.' ASME Journal of Mechanical Design, 135(10), p. 101003, Oct 2013. DOI: 10.1115/1.4024978

CCD impact example: robotic manipulator design

Sequential vs. CCD:

Sequential design result

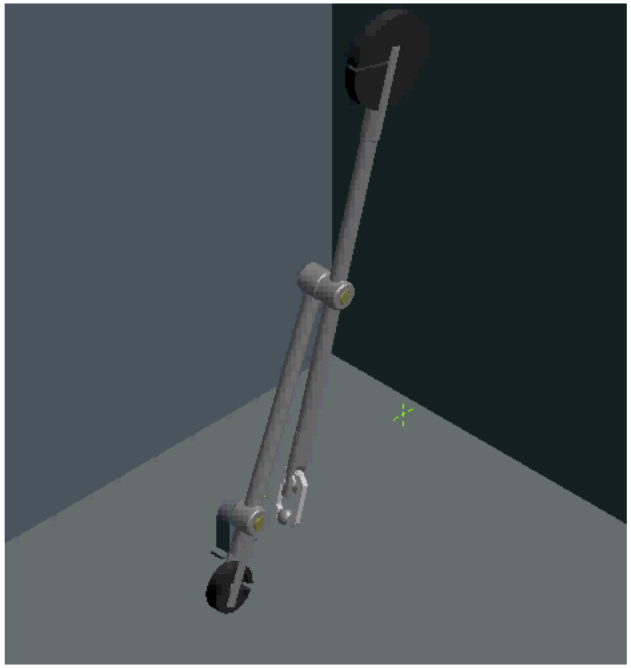


(link lengths) (offsets) (masses)

$\mathbf{x}_p = [1.0, 1.0, 0.3, 0.3, 10, 10\ ]^T$

$E(\mathbf{x}_p, \mathbf{x}_c) =$ **27.6 Joules**

CCD design result



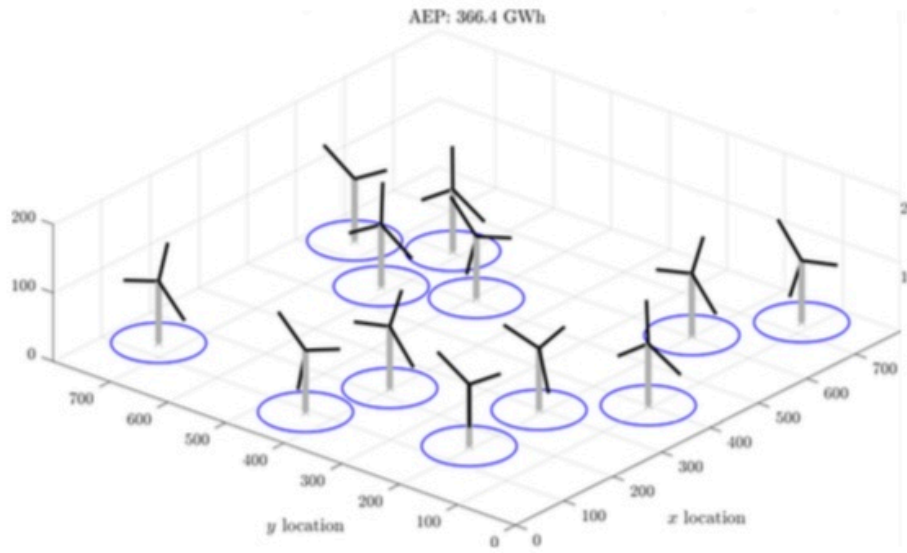
(link lengths) (offsets) (masses)

$\mathbf{x}_p = [0.838, 0.711, 0.216, 0.885, 3.89, 20.7]^T$

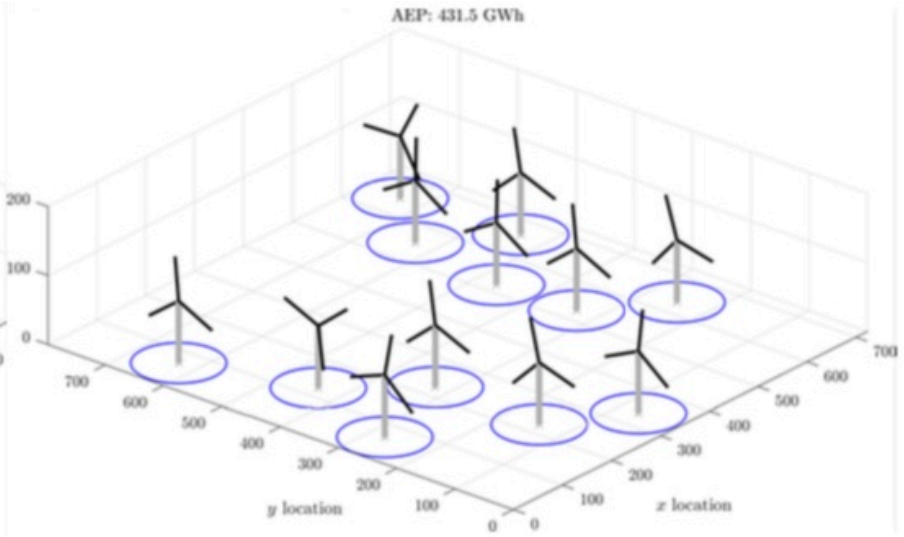
$E(\mathbf{x}_p, \mathbf{x}_c) =$ **5.86×10^{-5} Joules**

- **Passive dynamics tailored** to reduce control effort, complexity, and energy requirements for a pick-and-place task
- CCD can **exploit synergy** between passive dynamics and control system design

CCD impact example: combined wind turbine layout and hierarchical control (with APC for freq. reg.)



Layout only (AEP: 366.4 GWh)



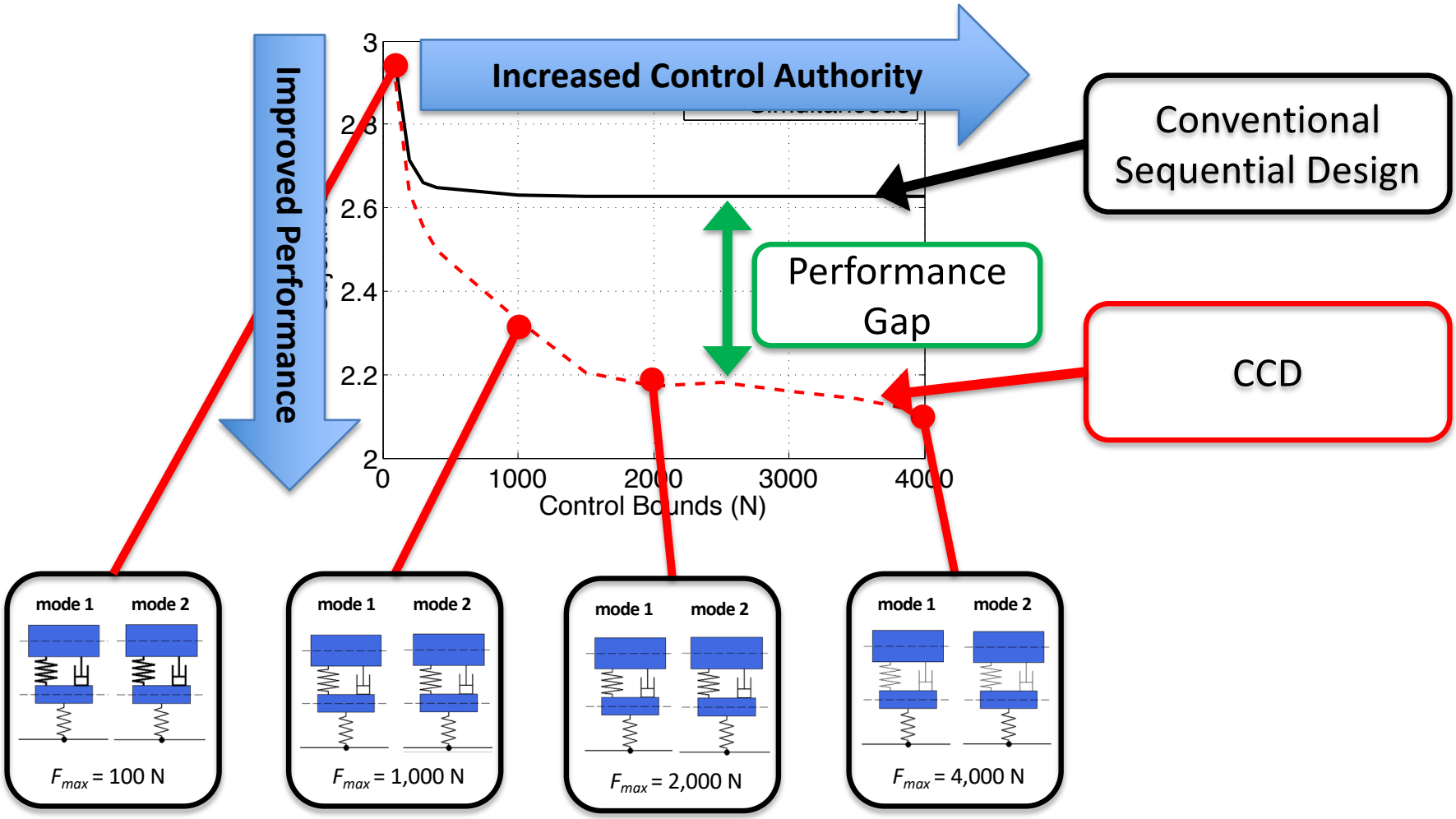
Layout + Control (AEP: 431.5 GWh)

Layout + Control AEP: **+ 17.7 %** ⇑

Anand P Deshmukh, James T Allison. 'Unrestricted Wind Farm Layout Design with Optimal Control Considerations.' In ASME 2017 International Design Engineering Technical Conferences, DETC2017-67480, p. V02AT03A021, Cleveland, OH, USA, Aug 2017. DOI: 10.1115/DETC2017-67480

Parametric study on control authority

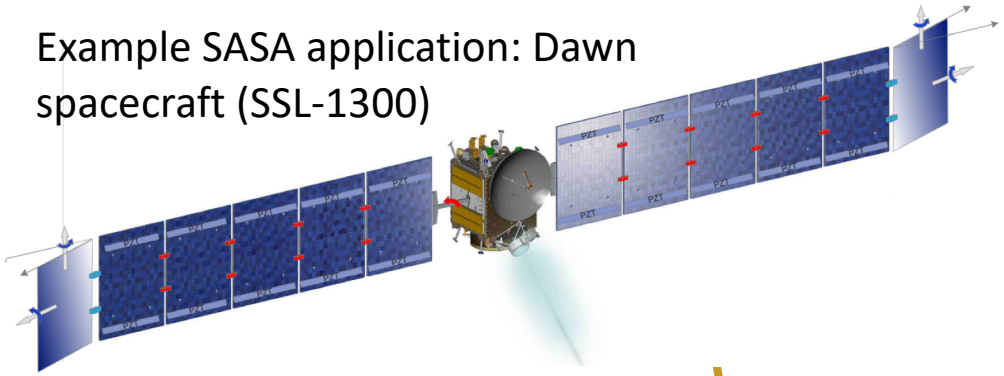
- Performance increases with allowed control force (increase in cost)
- Evidence of strong design coupling: 1) optimal plant design changes when control bound varied, 2) large gap in performance between sequential/simultaneous approaches

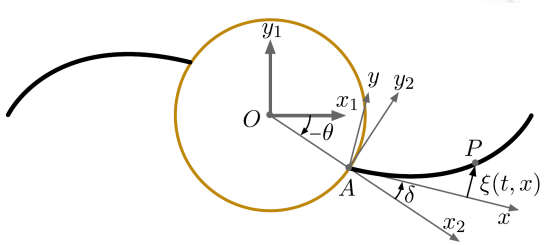


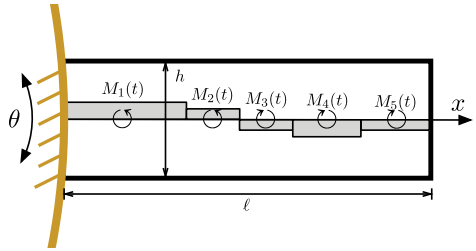
James T Allison, Tinghao Guo, Zhi Han. 'Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization.' ASME Journal of Mechanical Design, 136(8), p. 081003, Aug 2014. DOI: 10.1115/1.4027335

CCD impact example: Intelligent Structures for Spacecraft Attitude Control

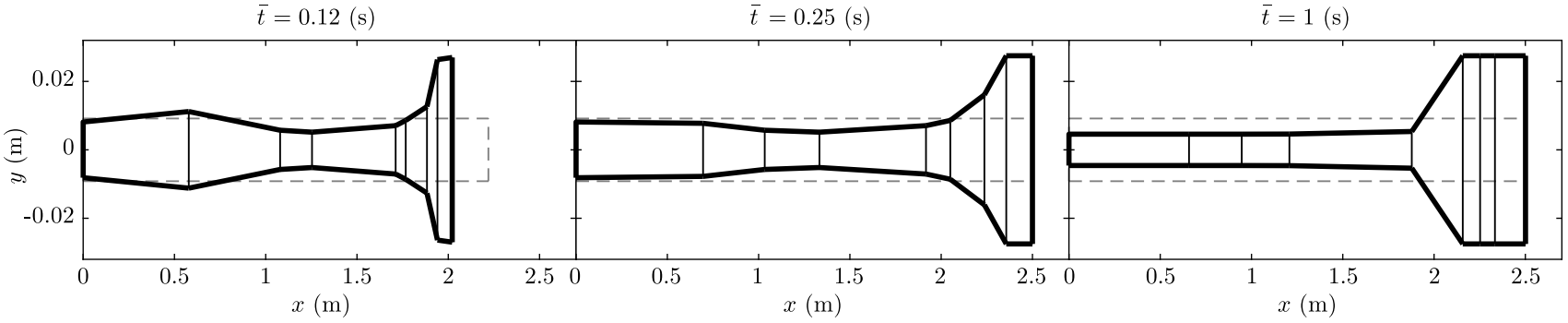
Example SASA application: Dawn spacecraft (SSL-1300)







Not Drawn to Scale, y axis $\approx 25\times$ magnification



Christian M Chilan, Daniel R Herber, Yashwanth Kumar Nakka, Soon-Jo Chung, James T Allison, Jack B Aldrich, Oscar S Alvarez-Salazar. 'Co-Design of Strain-Actuated Solar Arrays for Spacecraft Precision Pointing and Jitter Reduction.' AIAA Journal, 55(9), pp. 3180-3195, Sep 2017.

CCD impact example: Intelligent Structures for Spacecraft Attitude Control

MSAC: Standalone 3-axis ACS, arbitrarily large reorientations, > 1 degree/second

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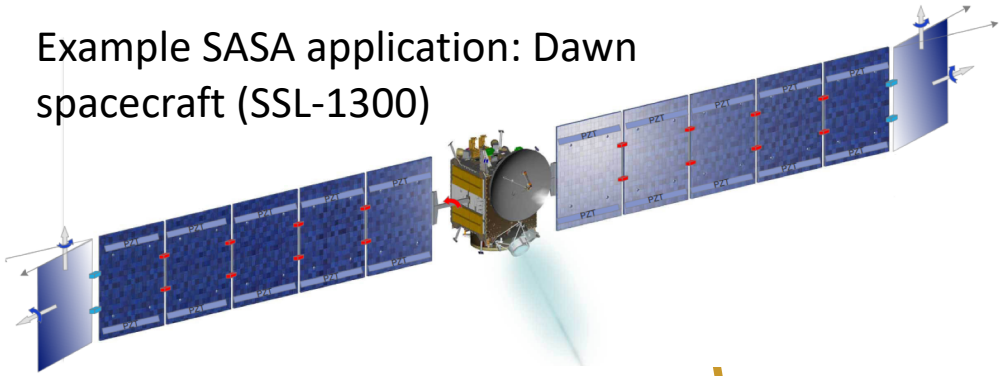
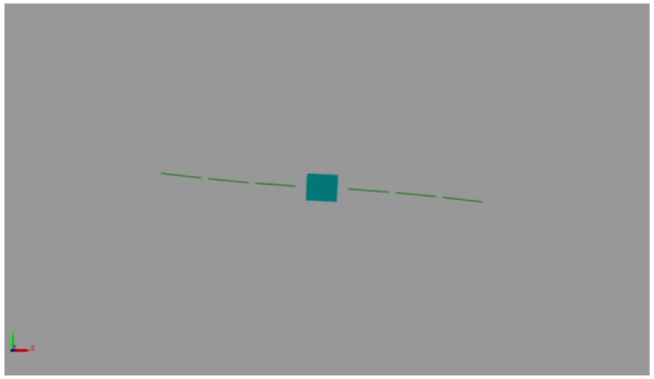
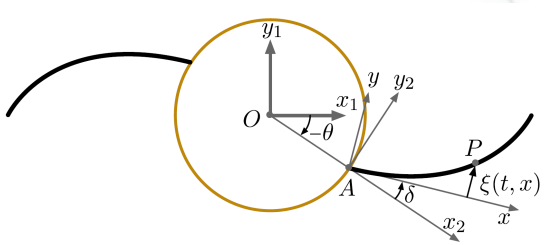
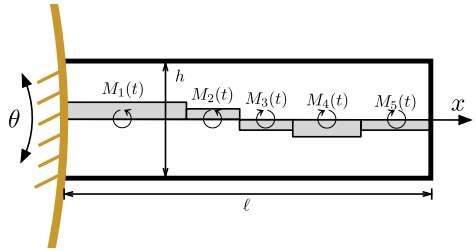


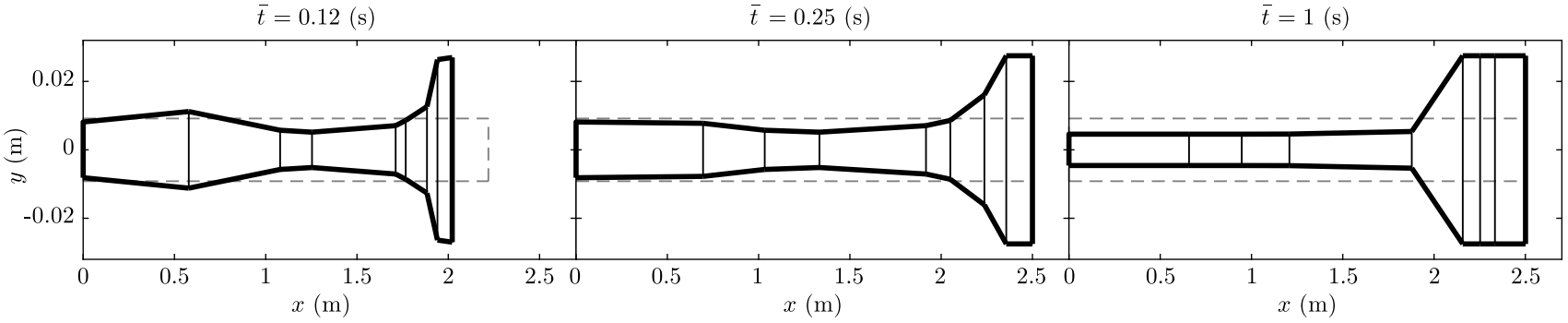






Vedant, James T Allison. 'Multifunctional Structures for Attitude Control.' In ASME Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2019-5565, Sep 2019.

Not Drawn to Scale, y axis $\approx 25\times$ magnification



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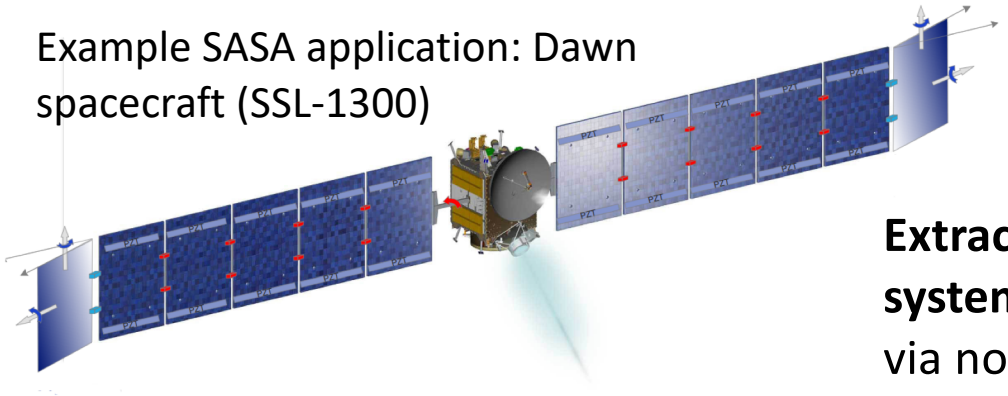
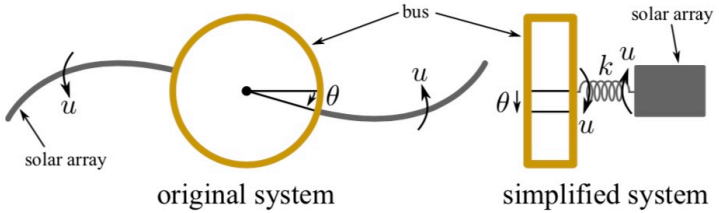




Extracting design rules for unprecedented systems from CCD data: Design rules identified via non-dimensional SASA CCD study

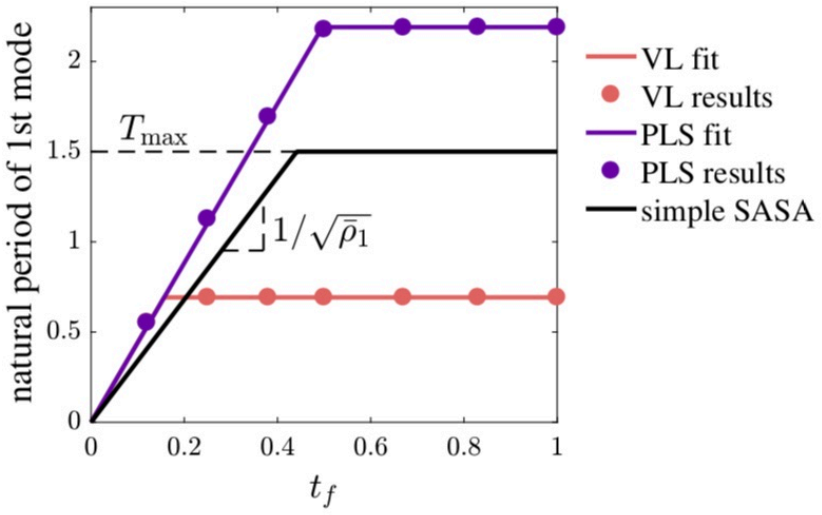
$$\min_{k,\bar{u}(\bar{t})} \quad -\frac{u_{\max} t_f^2}{4\pi^2 J}\bar{\theta}(2\pi)$$

$$\text{subject to:} \quad \bar{\theta}'' = -\frac{k t_f^2}{4\pi^2 J}\bar{\theta} + \bar{u}$$

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

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

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



Daniel R Herber, James T Allison. 'Unified Scaling of Dynamic Optimization Design Formulations.' In ASME 2017 International Design Engineering Technical Conferences, DETC2017-67676, p. V02AT03A003, Cleveland, OH, USA, Aug 2017. DOI: 10.1115/DETC2017-67676

What is Control Co-Design (CCD)?

Historical CCD Development

Current CCD State-of-the-Art

CCD Impact and Open Questions

Early Integrated Design Methods

- 1980's-1990's: Control Structure Interaction (CSI)
- 1980's-present: Multidisciplinary Design Optimization (MDO)

Initial CCD Research

- Late 1990's/early 2000's: CCD theory and method development, based on: unidirectional design coupling, LQR/G
- Cannot account for plant design in a comprehensive manner (e.g., failure modes, such as stress/temperature, requiring inequality path constraints)

Breakthrough: Direct Optimal Control in CCD

- 2011: First publication of CCD with DT, comprehensive plant design
- Numerically efficient, scalable method development
- 2017: Revised CCD theory for bi-directional problems

CCD Method Maturation and Impact

- Expanded applications, growing impact (key element of new research programs – NSF and ARPA-E)
- Still significant open questions (e.g., CCD with implementable CLC)

What is Control Co-Design (CCD)?

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CCD Impact and Open Questions

CCD State-of-the-Art

- Methods based on direct optimal control are quite **mature**
- Recent CCD methods account fully for **bi-directional** plant-control design coupling
- Requires **predictive models** that are appropriate for CCD studies (different that models used for control design alone)
- Appropriate for **early-stage design** studies (what would the best possible passive dynamic properties be?)
- Significant advances made in **numerical efficiency**, including for solving CCD problems with higher-fidelity models
- **General software tools** currently in development (supported by ARPA-E)
- Many **open questions** exist for CCD, especially when supporting higher-TRL development efforts

General CCD Formulation

- General co-design problems are nonlinear dynamic optimization problems:

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

$$\text{subject to:} \quad \dot{\boldsymbol{\xi}} - \boldsymbol{f}\left(t, \boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p\right) = \boldsymbol{0} \qquad \text{(dynamics)}$$

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

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

- Optimality conditions for the simultaneous approach with $\boldsymbol{x}_c := \boldsymbol{u}$, derived with Pontryagin's minimum principle[1]:

$$\dot{\boldsymbol{\lambda}}^* = -\left[\frac{\partial H}{\partial \boldsymbol{\xi}}\right]^*, \quad \boldsymbol{0} = \left[\frac{\partial H}{\partial \boldsymbol{u}}\right]^*$$

$$0 = \left[\boldsymbol{\mu}^T \boldsymbol{C}\right]^*, \quad 0 = \left[\boldsymbol{\nu}^T \boldsymbol{\phi}\right]^*, \quad \boldsymbol{\mu}^* \geq \boldsymbol{0}, \quad \boldsymbol{\nu}^* \geq \boldsymbol{0}$$

$$\boldsymbol{0} = \left[\boldsymbol{\lambda} + \frac{\partial \mathcal{M}}{\partial \boldsymbol{\xi}} + \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{\xi}}\right]_{t_0}^*, \quad \boldsymbol{0} = \left[\boldsymbol{\lambda} - \frac{\partial \mathcal{M}}{\partial \boldsymbol{\xi}} - \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{\xi}}\right]_{t_f}^*$$

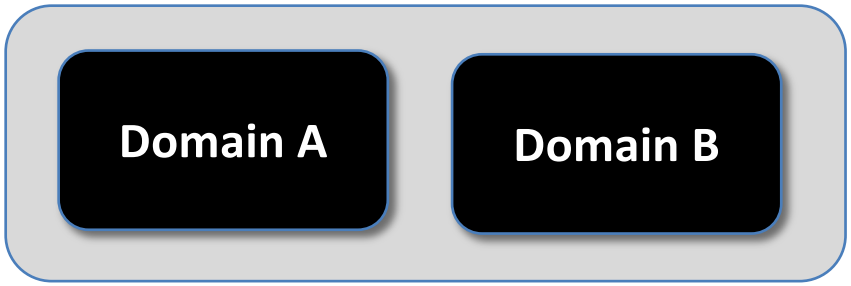
$$\boldsymbol{0} = \left[\frac{\partial \mathcal{M}}{\partial \boldsymbol{x}_p} + \boldsymbol{\nu}^T \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{x}_p}\right]_{t_0}^* + \int_{t_0}^{t_f} \left[\frac{\partial \mathcal{L}}{\partial \boldsymbol{x}_p} + \boldsymbol{\lambda}^T \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}_p} + \boldsymbol{\mu}^T \frac{\partial \boldsymbol{C}}{\partial \boldsymbol{x}_p}\right]^* dt$$

Design Coupling

Design Optimization Approach for Quantifying Design Coupling

If we make changes in one design domain, does that influence how we ***should*** make decisions in other domains?

- Suppose we have two design domains:



$$\mathbf{x} = [\mathbf{x}_A, \mathbf{x}_B]$$

$$f([\mathbf{x}_A, \mathbf{x}_B])$$

- If we make specify the design in domain *A*, how ***should*** we design domain *B* to obtain the best possible design?

Given a value for $\mathbf{x}_A$, we should choose a value for $\mathbf{x}_B$ that solves the following:

$$\begin{aligned} \min_{\mathbf{x}_B} \quad & f([\mathbf{x}_A, \mathbf{x}_B]) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x}) \leq \mathbf{0} \\ & \mathbf{h}(\mathbf{x}) = \mathbf{0} \end{aligned}$$

That is, given $\mathbf{x}_A$, choose the design for domain *B* to be: $\mathbf{x}_{B*}$

Design Optimization Approach for Quantifying Design Coupling

If we make changes in one design domain, does that influence how we ***should*** make decisions in other domains?

Let's answer this question more completely:

- If we change the design in domain *A*, how ***should*** we design domain *B* to obtain the best possible design?

Change in design domain *A*: $\Delta \mathbf{x}_A$

Required design in domain B
to optimize system performance: $\mathbf{x}_{B*}$

How might we quantify the strength of coupling between domains?

- Scalar case: $x_A, x_B \in \mathbb{R}$ Design coupling strength: $\dfrac{\partial x_{B*}}{\partial x_A}$

Design coupling strength: varies with location in the design space

Quantification of Plant and Control Design Coupling

Design Coupling Quantification in Co-Design

- Coupling strength: $\frac{\partial x_{p*}}{\partial x_c}$ or $\frac{\partial x_{c*}}{\partial x_p}$
- Varies across design space

Simple co-design example:

- Small dimension for visualization (single state, single control input)
- Non-trivial problem
- LQR used to solve optimal control (full-state feedback: *K*)

$$\min_{b,K} \quad \frac{w_c}{\xi_0^2}\int_0^\infty \left(q\xi^2 + ru^2\right)dt + w_p b$$

$$\text{subject to:} \quad \dot{\xi} = -b\xi + u$$

$$\phi_1 := \xi(0) - \xi_0 = 0$$

$$\phi_2 := -b \le 0,\ \phi_3 := -K \le 0$$

$$u = -K\xi,\ b \in \boldsymbol{x}_p,\ \text{and}\ K \in \boldsymbol{x}_c$$

Daniel R Herber, James T Allison. 'Nested and Simultaneous Solution Strategies for General Combined Plant and Control Design Problems.' ASME Journal of Mechanical Design, 141(1), p. 011402, Jan 2019. DOI: 10.1115/1.4040705

Design Coupling Quantification in Co-Design

Comparative solution method visualization:

- Iterated sequential, simultaneous, nested co-design
- Single plant design variable (*b*), single control design variable (*K*)
- Visualize solution in 2D design space via animation

$$\min_{b,K} \quad \frac{w_c}{\xi_0^2}\int_0^\infty \left(q\xi^2 + ru^2\right)dt + w_p b$$

$$\text{subject to:} \quad \dot{\xi} = -b\xi + u$$

$$\phi_1 := \xi(0) - \xi_0 = 0$$

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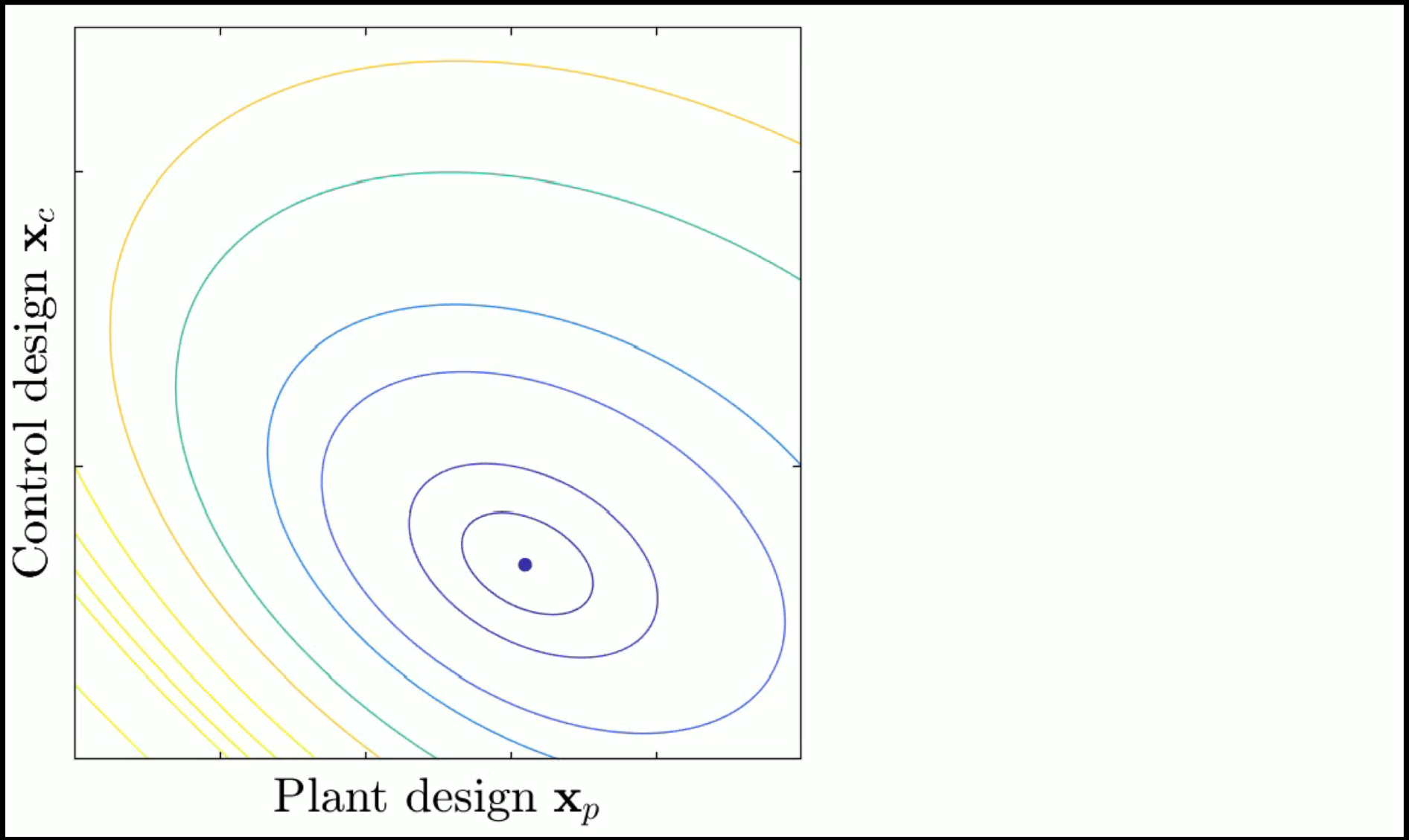
Example: Moderate Design Coupling



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Role of CCD/Design Automation in New ARPA-E Programs

Mario Garcia-Sanz:

- Faculty at Case Western Reserve, EECS
- Extensive experience in wind energy systems (controls)
- Independently recognized control-plant design coupling, informally used design coupling to reduce LCOE
- Upon becoming an ARPA-E program director, read **Prof. Dan Herber's** dissertation:

Daniel R Herber. 'Advances in Combined Architecture, Plant, and Control Design.' PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, USA, Dec 2017.

- Formalized what Mario has been doing for years
- Multiple new ARPA-E programs now based on CCD/other design automation methods

ARPA-E ATLANTIS Program: Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control

*The program encourages the application of **control co-design** (CCD) methodologies that integrate all relevant engineering disciplines at the start of the design process, with feedback control and dynamic interaction principles as the primary drivers of the design. CCD methodologies enable designers to analyze the interactions of FOWTs' aero-, hydro-, elastic-, electric-, economic-, and servo-system dynamics, and propose solutions that **permit optimal FOWT designs not achievable otherwise**.*

ARPA-E ATLANTIS and CCD

Three ATLANTIS project types:

1. New design development (New FOWT architecture)
2. Design tool creation (support CCD of new designs)
3. Empirical data acquisition (tool/design validation)

- Tight integration between project areas
- Design tools and new design methods are central
- Plans for CCD short courses to ramp up all ATLANTIS teams on relevant design methods
- Design automation momentum at ARPA-E (hydrokinetics, power electronics, carbon capture)

DEPARTMENT OF ENERGY ANNOUNCES $28 MILLION FOR OFFSHORE WIND ENERGY

ARPA-E Provides Funding for Pioneering Floating Turbine Designs

WASHINGTON, D.C. — The U.S. Department of Energy today announced up to $28 million in funding for a new Advanced Research Projects Agency-Energy (ARPA-E) program, Aerodynamic Turbines, Lighter and Afloat, with Nautical Technologies and Integrated Servo-control (ATLANTIS). ATLANTIS projects will develop new technologies for floating, offshore wind turbines (FOWTs) using the discipline of control co-design (CCD).

https://arpa-e.energy.gov/?q=news-item/department-energy-announces-28-million-offshore-wind-energy

Advanced Control for Applications:
ENGINEERING AND INDUSTRIAL SYSTEMS

EDITOR VIEWPOINT

Control Co-Design: an engineering game changer

Mario Garcia-Sanz

First published: 03 September 2019 | https://doi.org/10.1002/adc2.18

https://doi.org/10.1002/adc2.18

DEPARTMENT OF ENERGY ANNOUNCES $28 MILLION FOR OFFSHORE WIND ENERGY

Take-Aways:

- Years of basic work by a range of groups on the foundations of control co-design
- Managed to capture the attention of some of the right people
- Significant government resources committed, potential to realize substantial societal impact made possible by engineering design research
- What are the best ways forward? Fill important gaps, strategic collaborations?

https://doi.org/10.1002/adc2.18

CCD Open Questions

- Deeper study and development of strategies to **include CLC in CCD**, balancing design flexibility and implementability/stability/robustness
- Account for **uncertainty** in the presence of design coupling (different from existing RBDO or robust or stochastic control)
- Incorporation with **human-directed design** activities
- Extension to **large-scale systems** (distributed optimization)
- Link with **physical experiments** (e.g., CCD method validation, HIL replaces simulation for part of the CCD optimization problem)
- How do we maximize intellectual, practical, and societal **impacts** moving forward with CCD?

Upcoming NSF Workshop on CCD:

March 26-27, 2020
UIUC
(Jointly supported by EDSE and DCSD)

Conclusion

Conclusion

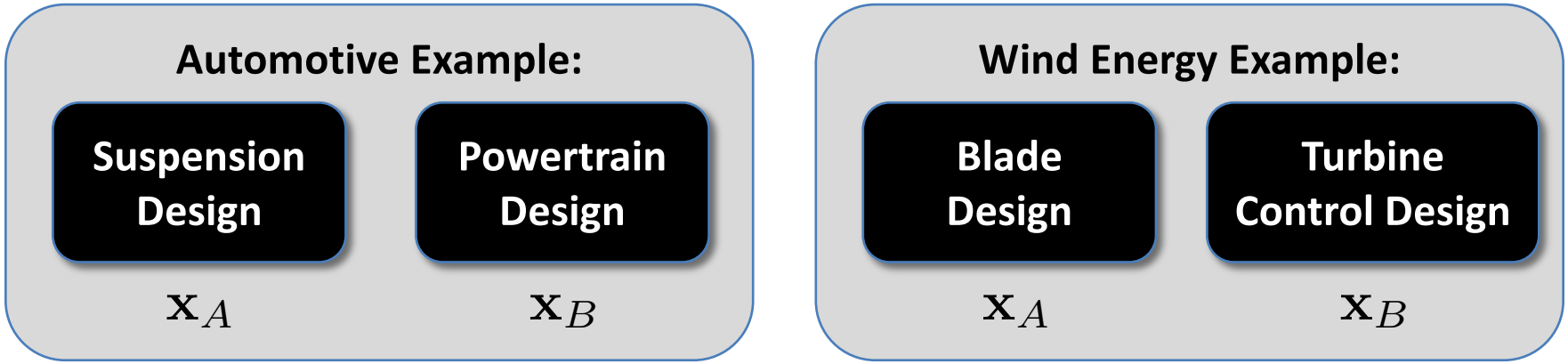
- Significant performance improvements are often possible for actively controlled engineering systems via exploitation of plant-control design coupling
- CCD methods using OLOC are fairly mature, and can provide valuable insights at early design stages
- CCD has gained significant attention recently from funding agencies, and now is an opportunity to pursue strategic collaborations to maximize impact
- Several open questions exists that are intellectually rich and important to engineering practice

Appendix

Design Coupling

Design coupling is not the same as physics coupling

- Two or more distinct design domains (sets of decision variables):



- Suppose the set of design variables (e.g., geometric parameters, control gains, etc.) is naturally partitioned into two or more sets:

$$\mathbf{x} = [\mathbf{x}_A, \mathbf{x}_B]$$

- If we make changes in one design domain, does that influence how we ***should*** make decisions in other domains?

What was missing?

MDO:

- Established principles for managing physics and design coupling, but very little done to address specific challenges/use specific tools for active control

CSI:

- Primarily focuses on reducing control-structure interaction, although a few studies addressed tailoring passive dynamics to our advantage
- Very specific application domain – not general theory/methods

Initial Co-Design Research:

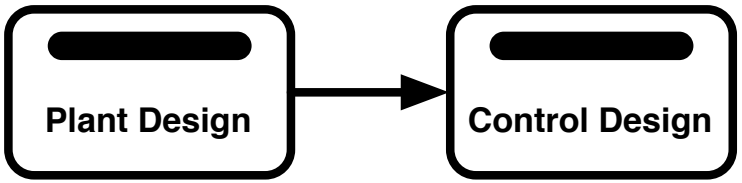
- General theory and methods developed from a controls-centric perspective
- Only applicable to problems with very simplified treatment of plant design

Needs:

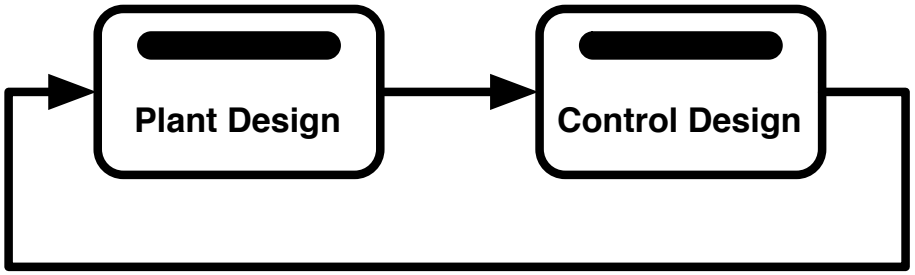
- General theory and tools for problems with more comprehensive treatment of physical system design (e.g., nonlinear failure mode constraints), nonlinear dynamics systems, and bi-directional design coupling
- Methods to understand, quantify, and explicitly capitalize on plant-control design coupling to advance system performance.

Design Process Options

Conventional Sequential Design



Iterated Sequential Design

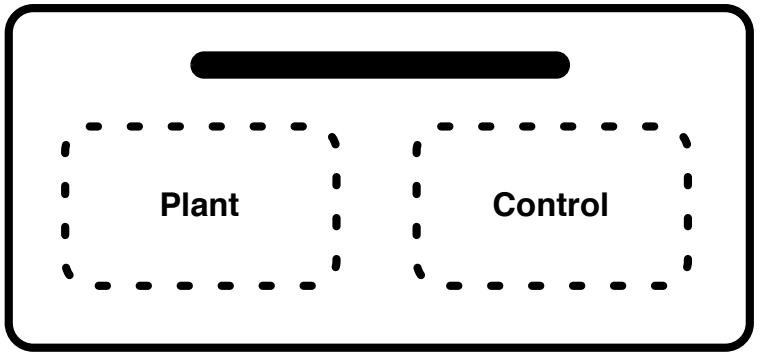


Mathematically-equivalent formulations studied to support practical solution of high-fidelity problems

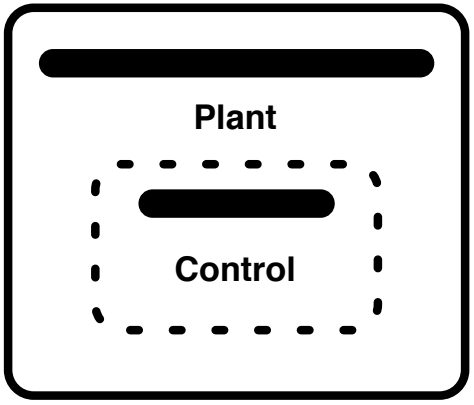
Co-Design

Integrated physical (plant) and control system design

Simultaneous Design



Nested Design



Distributed optimization is also an option

2009/2010 Breakthrough: Direct Optimal Control

- Time domain optimal control method, general nonlinear dynamic systems
- DT: Historically for chemical process control/trajectory optimization
- Supports bi-directional design coupling, use of comprehensive plant design models
- Enables computationally-efficient solution of co-design problems with realistic treatment of physical design

First publication of control co-design (CCD) method using direct transcription, applied to automotive suspension design:

James T Allison, Zhi Han. *'Co-design of an Active Suspension Using Simultaneous Dynamic Optimization.'* In ASME 2011 International Design Engineering Technical Conferences, DETC2011-48521, pp. 903-913, Washington, DC, USA, Aug 2011.

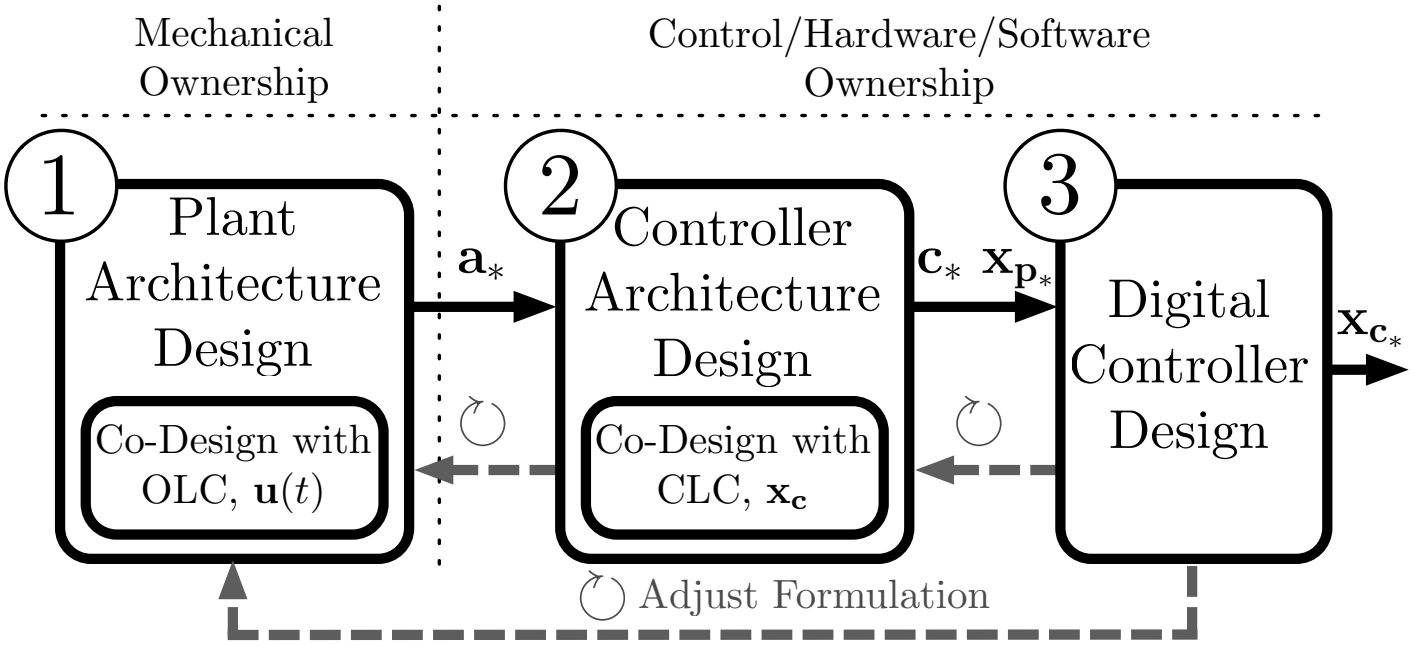
James T Allison, Tinghao Guo, Zhi Han. *'Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization.'* ASME Journal of Mechanical Design, 136(8), p. 081003, Aug 2014.

OLOC CCD Within Multi-Stage System Design Process

OLOC CCD in Multi-Stage Design

Bridging the gap to systems engineering practice:

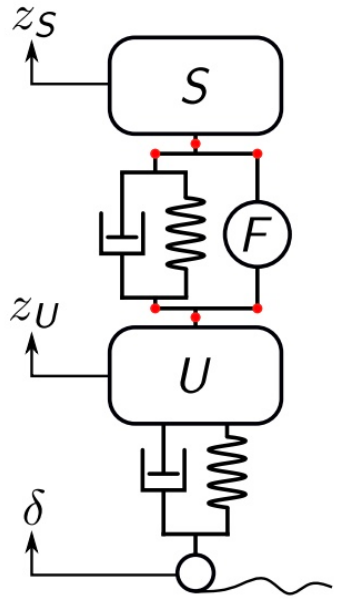
Concept: Use co-design for early-stage plant development, inform reformulation at later stages

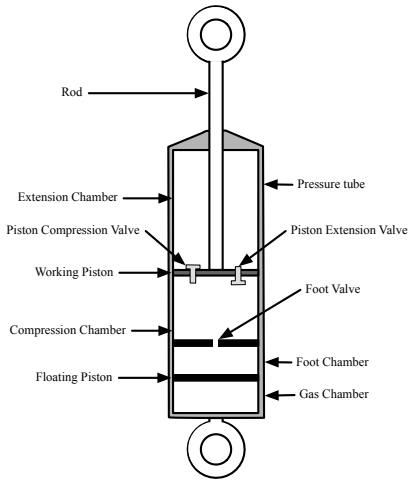


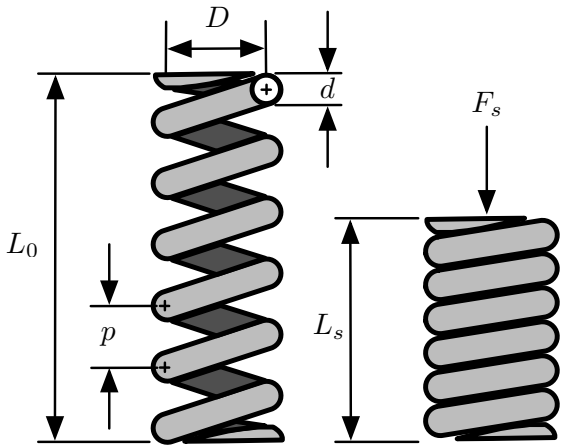
Anand P Deshmukh, Daniel R Herber, James T Allison. 'Bridging the Gap between Open-Loop and Closed-Loop Control in Co-Design: A Framework for Complete Optimal Plant and Control Architecture Design.' In 2015 American Control Conference, pp. 4916-4922, Chicago, IL, USA, Jul 2015. DOI: 10.1109/ACC.2015.7172104

Initial Co-Design Study: Active Suspension

- **Assumed architecture:** Canonical quarter-car model with force actuator
- **Co-design problem:** Optimize comfort and handling with respect to detailed damper and spring design variables (with detailed failure mode consideration), as well as force actuator trajectory (with simple bounds)
- **Solution method:** Tested both sequential and simultaneous methods, direct transcription solution approach





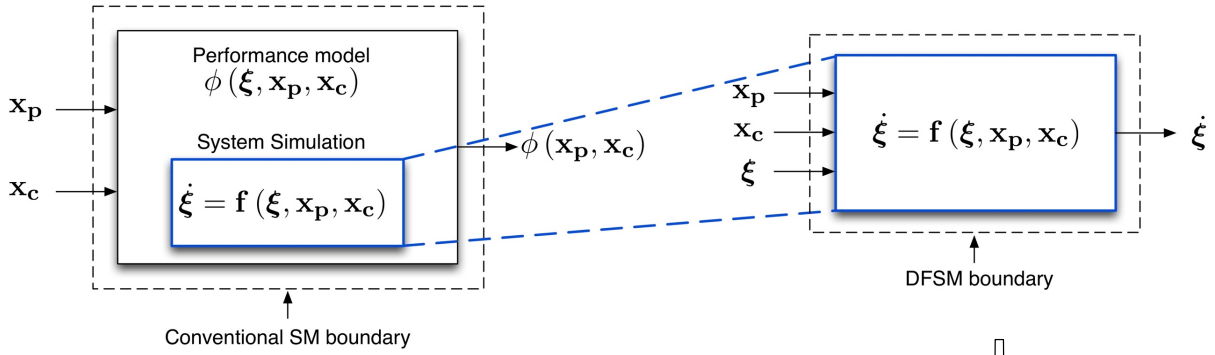


James T Allison, Tinghao Guo, Zhi Han. 'Co-Design of an Active Suspension Using Simultaneous Dynamic Optimization.' ASME Journal of Mechanical Design, 136(8), p. 081003, Aug 2014. [DOI: 10.1115/1.4027335

Single Turbine CCD: Horizontal Axis Wind Turbine (HAWT) Design Using Aero-servo-elastic Modeling

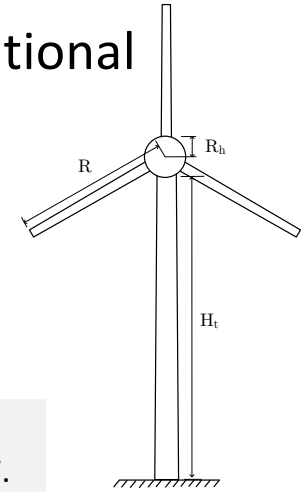
Enable use of higher-fidelity models using new surrogate modeling strategy specific for dynamic systems

- 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

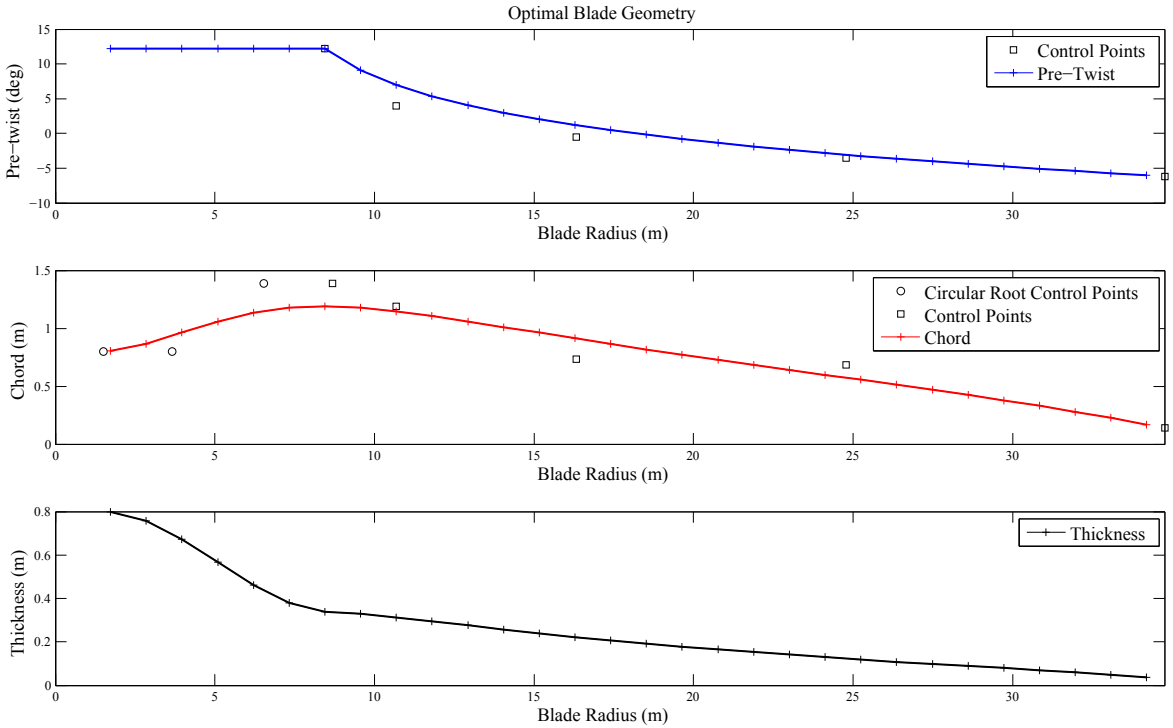
	DT using $\mathbf{f}(\cdot)$	DFSM using $\hat{\mathbf{f}}(\cdot)$	SM using $\hat{\phi}(\cdot)$
No. $\mathbf{f}(\cdot)$ evaluations	25160	2800	N/A
Solution time	419 min	124 min	618 min
FAST evaluation time	50.9%	18.8%	87.1%



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.

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

$\mathbf{x_{p_*}}$	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



Anand P Deshmukh, James T Allison. 'Multidisciplinary Dynamic Optimization of Horizontal Axis Wind Turbine Design.' Structural and Multidisciplinary Optimization, 53(1), pp. 15-27, Jan 2016. DOI: 10.1007/s00158-015-1308-y

Integrated Turbine Layout and Control

- Many previous studies have focused on layout alone without control, with varying levels of fidelity and assumptions [Tong et.al. 2014, Chowdhury et al., 2010,12,13, Chen and MacDonald, 2014, Turner 2014]
- Often turbine are assumed to be orthogonal to wind (no yaw)
- Fleming et. al. optimized layout and fixed yaw angles [2015]
- Synergy between yawing, rotor control and layout is missing

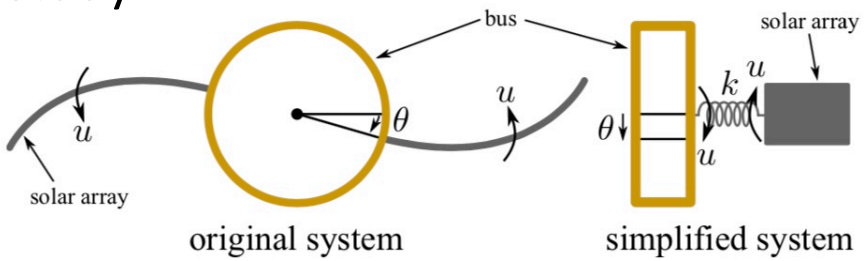
Our Approach:

- Layout design with control to exploit synergy layout/control.
- Continuous time-varying overlap areas considered
- Assumption: turbine count and farm site predetermined

Anand P Deshmukh, James T Allison. 'Unrestricted Wind Farm Layout Design with Optimal Control Considerations.' In ASME 2017 International Design Engineering Technical Conferences, DETC2017-67480,, Cleveland, OH, USA, Aug 2017. DOI: 10.1115/DETC2017-67480

Extracting generalizable rules from design data

- Optimal design trends observed as maneuver specifications adjusted
- Initial hypothesis was shown to be incorrect after performing design-focused scaling study



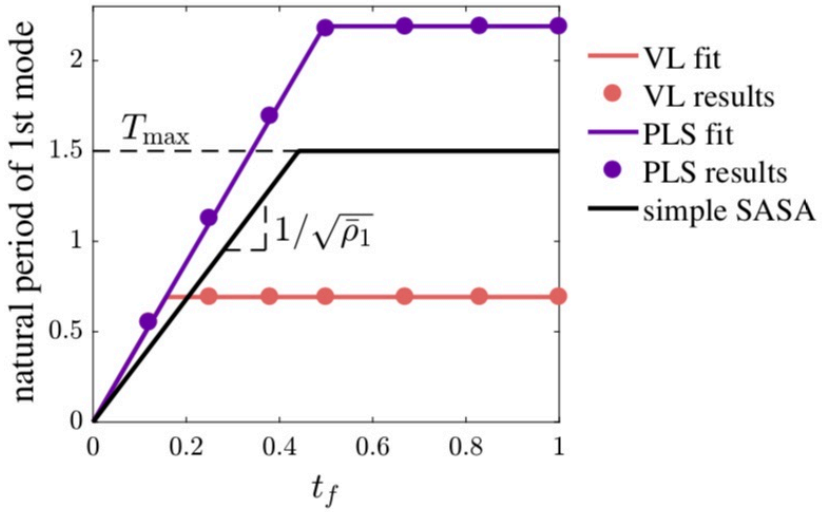
$$\min_{k,\bar{u}(\bar{t})} \quad -\frac{u_{\max} t_f^2}{4\pi^2 J}\bar{\theta}(2\pi)$$

$$\text{subject to:} \quad \bar{\theta}'' = -\frac{k t_f^2}{4\pi^2 J}\bar{\theta} + \bar{u}$$

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

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

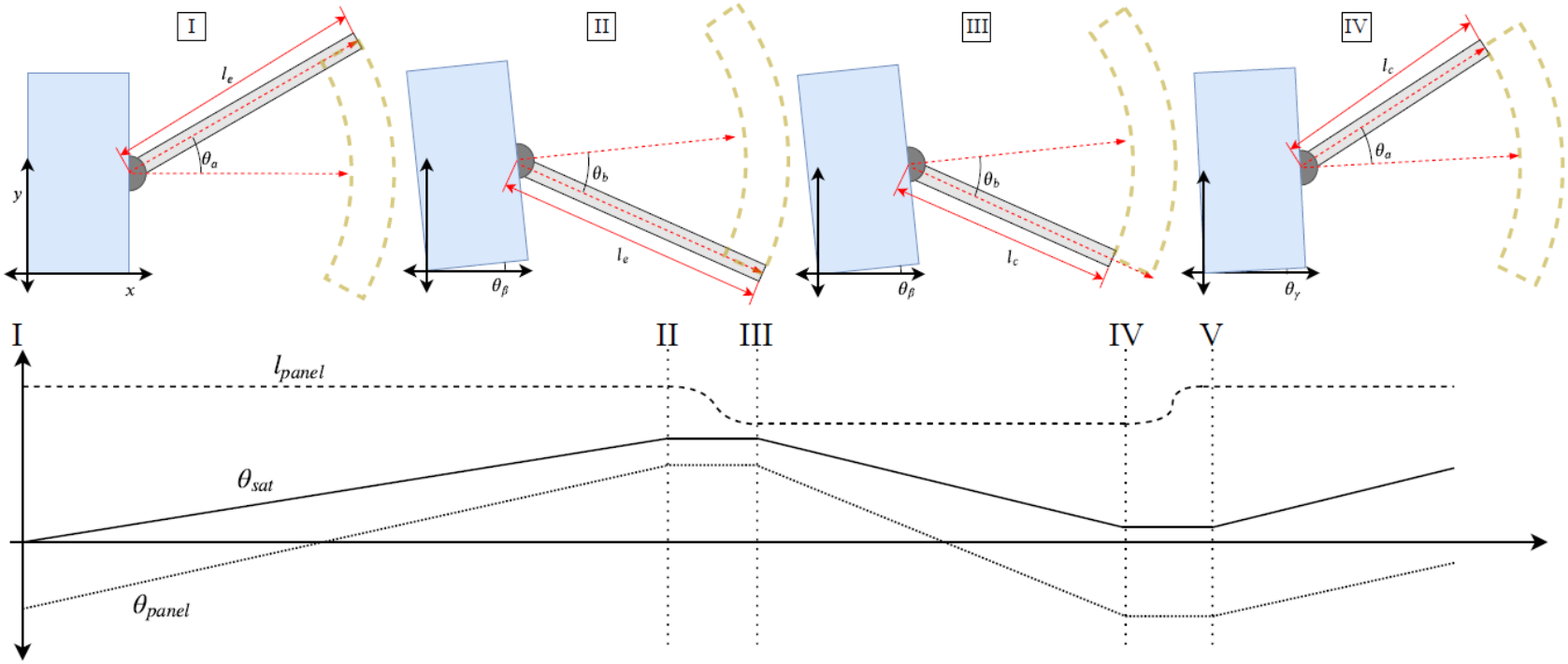
$$|\bar{u}(\bar{t})| \leq 1$$



Daniel R Herber, James T Allison. *'Unified Scaling of Dynamic Optimization Design Formulations.'* In ASME 2017 International Design Engineering Technical Conferences, DETC2017-67676, Cleveland, OH, USA, Aug 2017.

SASA Extension: Multifunctional Structures for Attitude Control

- Cycle with changes in mass moment of inertia enables net change in orientation with monolithic structures
- Frequency/displacement tradeoff: achieving ~1 deg/sec, < 100 W for practical systems (e.g., SSL-1300, PZT actuators)



Vedant, James T Allison. 'Multifunctional Structures for Attitude Control.' In ASME Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2019-5565, Louisville, KY, USA, Sep 2019.