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

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Daniel R. Herber[1] James T. Allison[2]

[1] Colorado State University
Department of Systems Engineering
daniel.herber@colostate.edu

[2] University of Illinois at Urbana-Champaign
Department of Industrial and Enterprise Systems Engineering
jtalliso@illinois.edu

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What is Control Co-design?

What is Control Co-Design (CCD)?

- **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
- Subset of **Multidisciplinary Design Optimization** (MDO) methods where at least one discipline is control-system design[1]

[1] Allison and Herber 2014

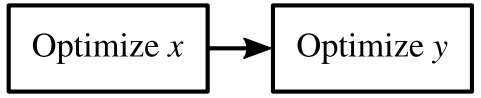
Design Optimization Across Two Disciplines

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

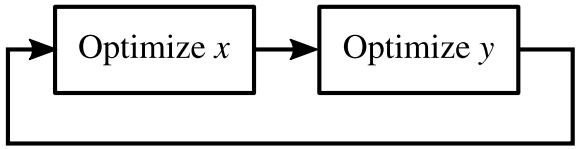
$$\begin{aligned} \min_{x,y} \quad & f_x(x) + f_y(y) + f_{xy}(x,y) \\ \text{subject to :} \quad & g_x(x) \leq 0,\ g_y(y) \leq 0 \\ & g_{xy}(x,y) \leq 0 \end{aligned}$$

- System optimality requires **simultaneous optimization** of x and y
- **Sequential design** does not produce system-optimal designs if cross terms exist[1] and is still largely used in practice
- Several formulations are mathematically equivalent* to simultaneous design[2]

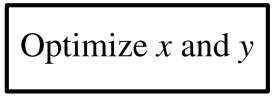
Sequential design



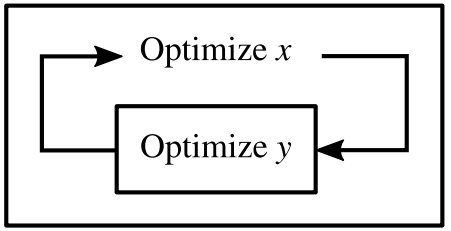
Iterated sequential design



Simultaneous design



Nested design

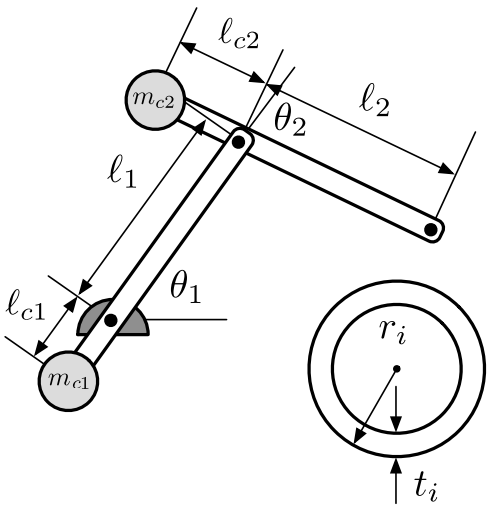


[1] Fathy et al. 2001; Allison, Guo, and Han 2014 [2] Fathy et al. 2001

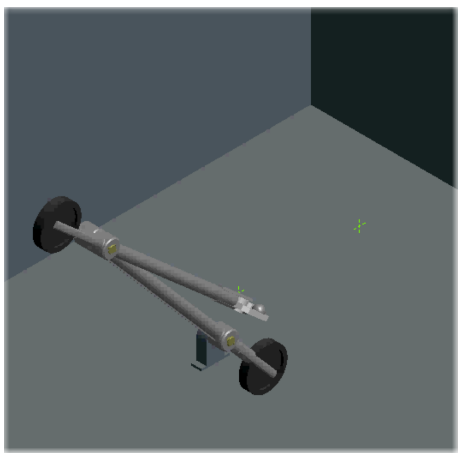
CCD Impact Examples

Robotic Manipulator Design

- **Passive dynamics** tailored to reduce control effort, complexity, and energy requirements for a pick-and-place task[1]
- CCD can **exploit synergy** between passive dynamics and control system design



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

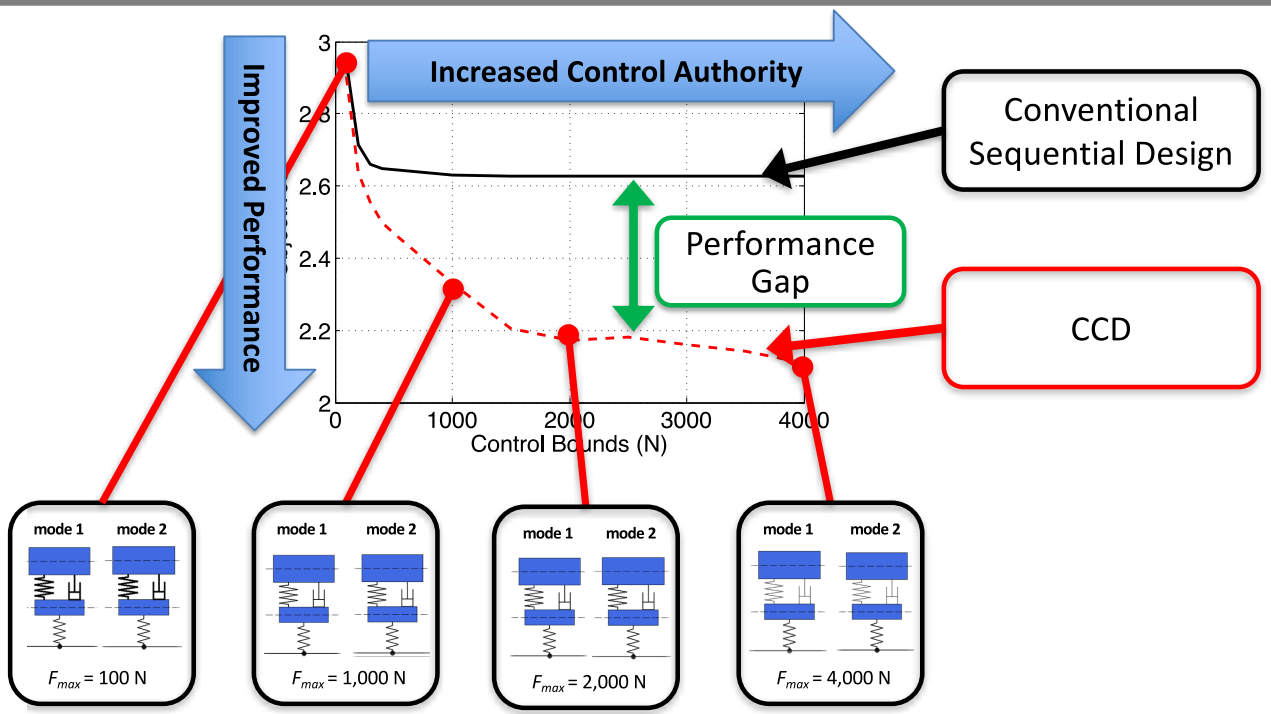
$E(\mathbf{x}_p, \mathbf{x}_c)$ = **5.86×10^{-5} Joules**

[1] Allison 2013

CCD Impact Examples (continued)

Active Vehicle Suspension using Direct Transcription

- Performance improvements with increasing control authority (but potential increases in cost)[1]
- Large **performance gap between sequential/simultaneous**



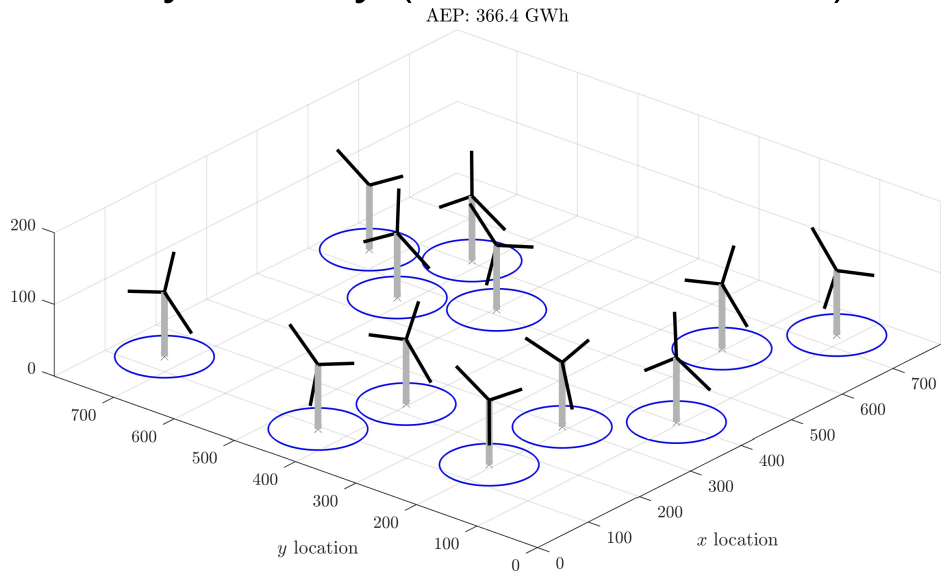
[1] Allison, Guo, and Han 2014

CCD Impact Examples (continued)

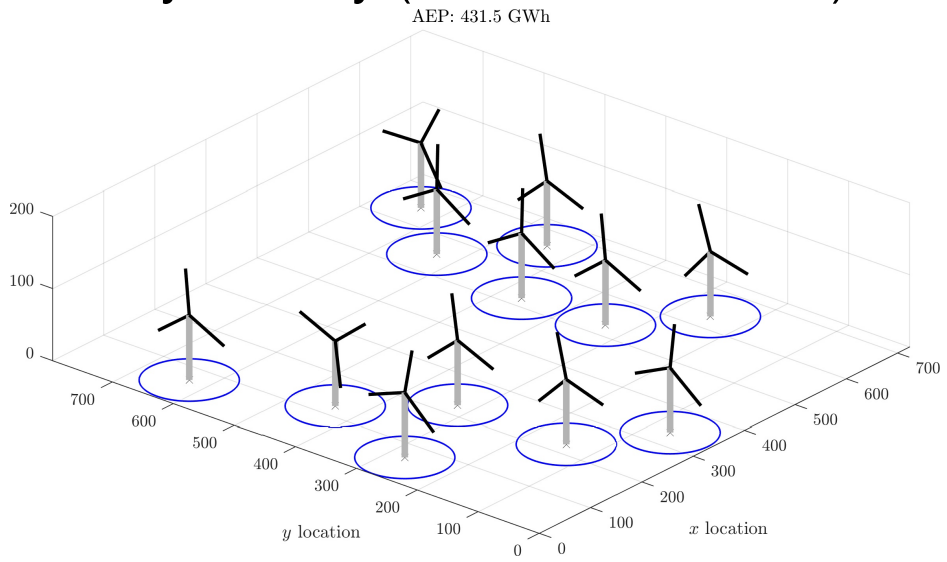
Combined Wind Turbine Layout and Hierarchical Control

- Layout and Control AEP increase of 17.7% over layout only[1]

Layout only (AEP: 366.4 GWh)



Layout only (AEP: 431.5 GWh)



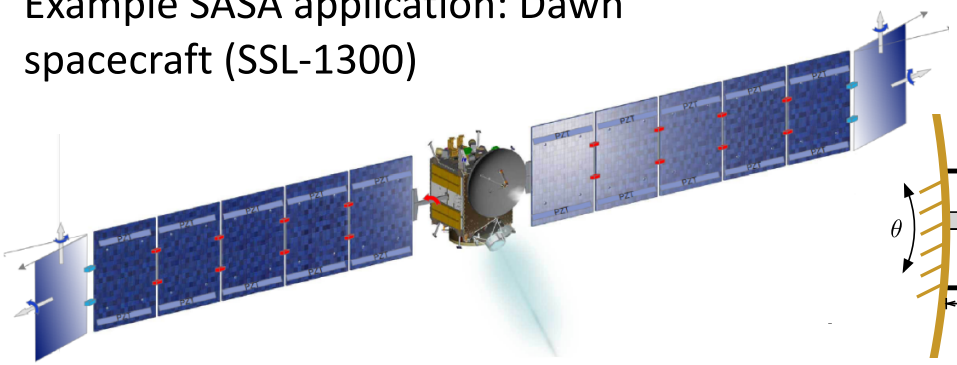
[1] Deshmukh and Allison 2017

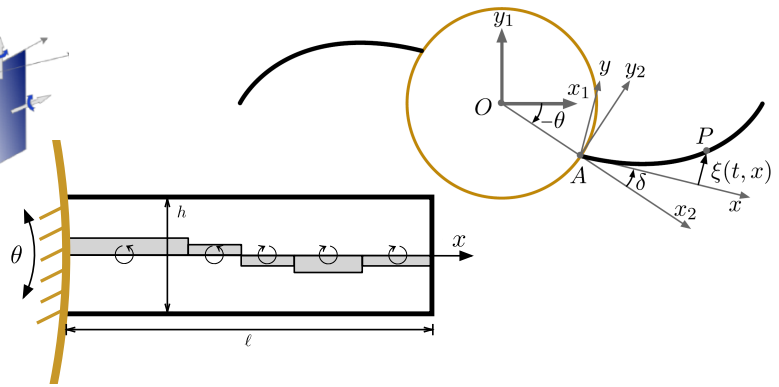
CCD Impact Examples (continued)

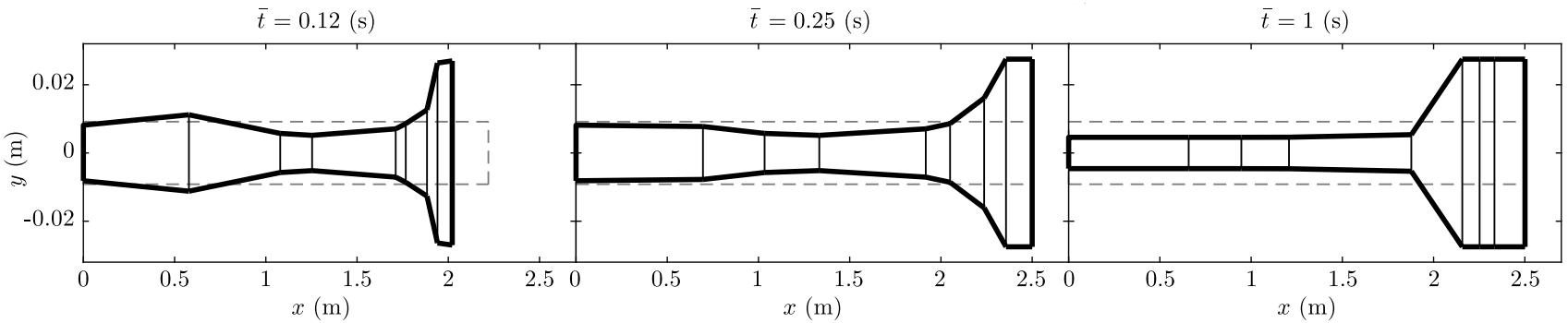
Intelligent Structures for Spacecraft Attitude Control

- Tailored structural properties with distributed control[1]
- Extracted **design rules** from CCD data[2]

Example SASA application: Dawn spacecraft (SSL-1300)







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

[1] Chilan et al. 2017; Vedant and Allison 2019 [2] Herber and Allison 2017

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Brief Overview of CCD Research

Historical CCD Development

Early Integrated Design Methods

- 1980's-1990's: Control Structure Interaction (CSI)[1]
- 1980's-present: Multidisciplinary Design Optimization (MDO)[2]

Initial CCD Research

Breakthrough: Direct Optimal Control in CCD

CCD Method Maturation and Impact

[1] Crawley and Luis 1987; Manning 1991; Rao and Sunar 1994 [2] Sobieszczanski-Sobieski and Haftka 1997; Martins and Lambe 2013

Historical CCD Development (continued)

Early Integrated Design Methods

Initial CCD Research

- Late 1990's/early 2000's: CCD theory and method development[1]
- Primarily based on unidirectional design coupling, LQR/G
- Cannot account for plant design in a comprehensive manner[2] (e.g., state-dependent failure modes)

Breakthrough: Direct Optimal Control in CCD

CCD Method Maturation and Impact

[1] Fathy et al. 2001; Reyer et al. 2001 Han 2014; Herber and Allison 2018

[2] Allison and Herber 2014; Allison, Guo, and

Historical CCD Development (continued)

Early Integrated Design Methods

Initial CCD Research

Breakthrough: Direct Optimal Control in CCD

- 2011: First publication of CCD with direct transcription (DT) enabling comprehensive plant design while being generally efficient and scalable[1]
- 2017: Revised CCD theory for bi-directional problems[2]

CCD Method Maturation and Impact

[1] Allison, Guo, and Han 2014 [2] Herber and Allison 2018

Historical CCD Development (continued)

Early Integrated Design Methods

Initial CCD Research

Breakthrough: Direct Optimal Control in CCD

CCD Method Maturation and Impact

- Expanded applications, growing impact (key element of new research programs – NSF and ARPA-E)[1]
- Labeled an engineering game changer[2]
- Still significant open questions[3]

[1] Slides 14 and 15 [2] Garcia-Sanz 2019 [3] Slide 13

CCD State-of-the-Art

- Recent CCD methods account fully for **bi-directional** plant-control design coupling[1]
- Requires **predictive models** that are appropriate for CCD studies[2] (different that models used for control design alone)
- Methods based on direct optimal control (direct transcription) are quite mature[3]
- Appropriate for **early-stage design** studies[4] (what would the best possible passive dynamic properties be?)
- **General software tools** currently in development (supported by ARPA-E[5])
- Many **open questions** exist for CCD, especially when supporting higher-TRL development efforts

[1] Allison, Guo, and Han 2014; Herber and Allison 2018 [2] Allison and Herber 2014 [3] Herber 2017; Allison, Guo, and Han 2014; Chilan et al. 2017 [4] Deshmukh, Herber, and Allison 2015 [5] ARPA-E 2019a

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CCD Open Questions and Impact

CCD Open Questions

- Deeper study and development of strategies to include **closed-loop control in CCD**[1], balancing design flexibility and implementability/stability/ robustness
- Account for **uncertainty** in the presence of design coupling[2] (some specific differences compared to existing RBDO or robust or stochastic control)
- Link with **physical experiments** (e.g., CCD method validation where HIL replaces simulation for part of the CCD optimization problem[3])
- Extension to **large-scale systems**[4] (distributed optimization)
- How do we maximize intellectual, practical, and societal **impacts** moving forward with CCD?

[1] Deshmukh, Herber, and Allison 2015; Nash and Jain 2020 [2] Cui, Allison, and Wang 2020; Azad and Alexander-Ramos 2020 [3] Deodhar, Deese, and Vermillion 2017
[4] Liu, Azarm, and Chopra 2020; Behtash and Alexander-Ramos 2020

→ CCD/Design Automation in New ARPA-E Programs

- DE-FOA-0002051: Aerodynamic Turbines, Lighter and Afloat, With Nautical Technologies and Integrated Servo-Control (ATLANTIS)[1]
  *"The program encourages the **application of control co-design (CCD)** methodologies . . . CCD methodologies enable designers to analyze . . . and propose solutions that **permit optimal FOWT designs not achievable otherwise**."*
- DE-FOA-0002220: Flexible Carbon Capture and Storage (FLECCS)[2]
  *"Applicants are thus encouraged to consider **advanced optimization techniques** that allow for a broader range of process configurations and **design and operational variables**. . ."*
- DE-FOA-0002334: Submarine Hydrokinetic And Riverine Kilo-megawatt Systems (SHARKS)[3]
  *"This Program is aimed at **applying Control Co-Design (CCD)**, Co-Design (CD) and Designing-for-OpEx (DFO) methodologies to HKT design."*
- Takeaway: **Significant government resources committed, potential to realize substantial societal impact**

[1] ARPA-E 2019a [2] ARPA-E 2019b [3] ARPA-E 2020

NSF Workshop on CCD

- Organized by James Allison (UIUC) and Chris Vermillion (North Carolina State University)
- Workshop on **Integrated Design of Active Dynamic Systems (IDADS)** supported by NSF (EDSE and DCSD programs)
- Focusing on bringing together a diverse set of viewpoints related to the topic of CCD
- **Online meeting was held March 26, 2020**
- In-person workshop will be held at a later date
- Workshop website: **http://conferences.illinois.edu/idads2020**

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Questions?

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Daniel R. Herber
Colorado State University
daniel.herber@colostate.edu
www.engr.colostate.edu/~drherber

James T. Allison
University of Illinois at Urbana-Champaign
jtalliso@illinois.edu
www.systemdesign.illinois.edu