Experimentally Infused Co-Design with Application to Airborne Wind Energy Systems

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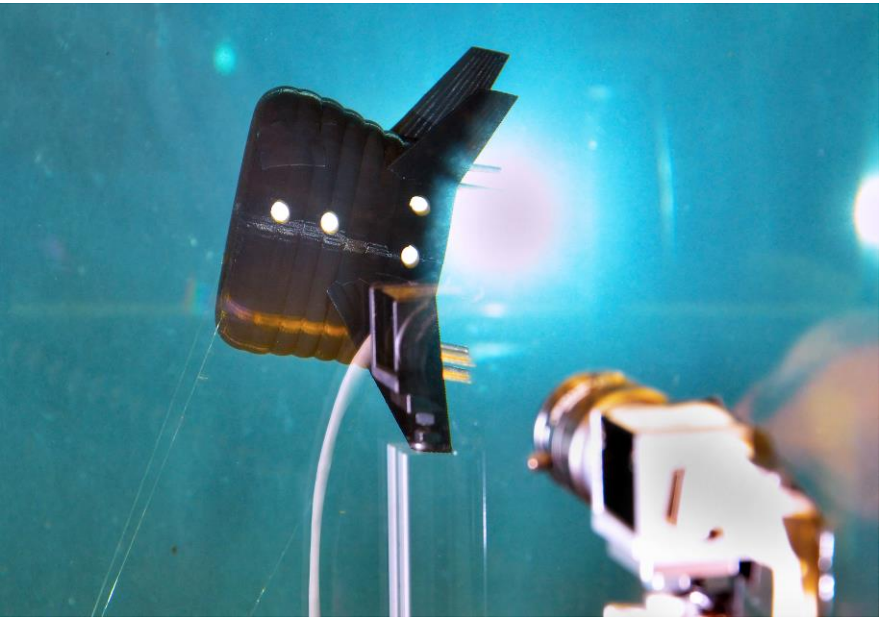
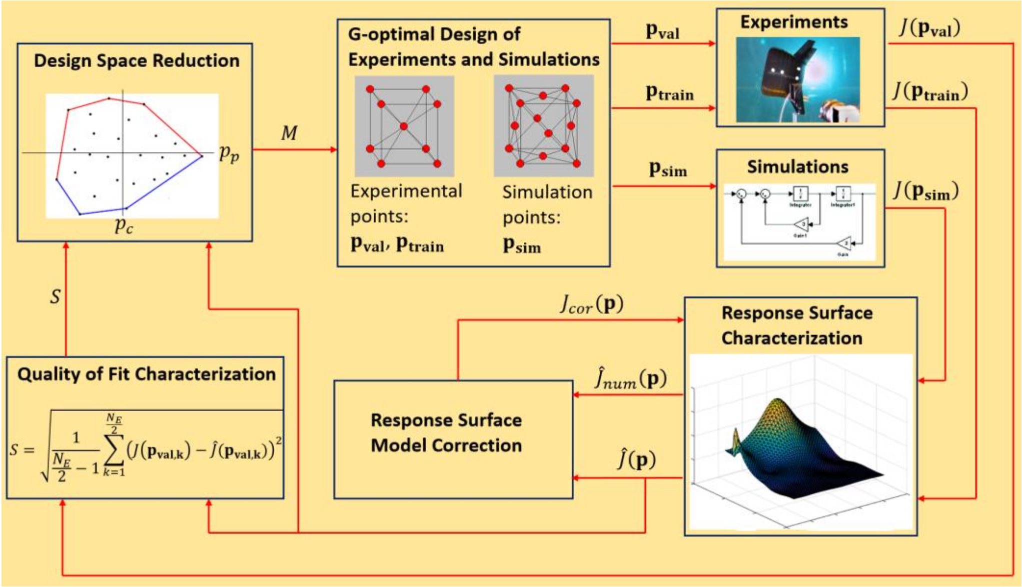
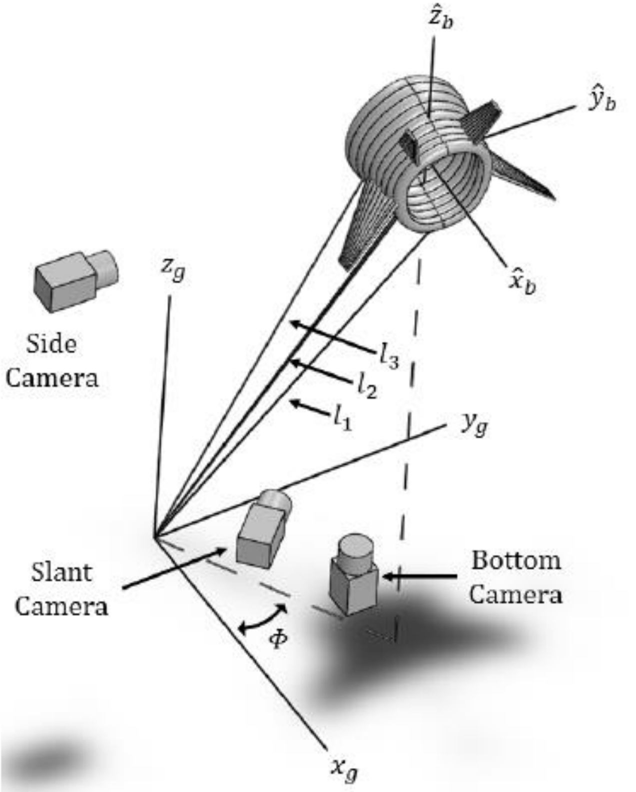




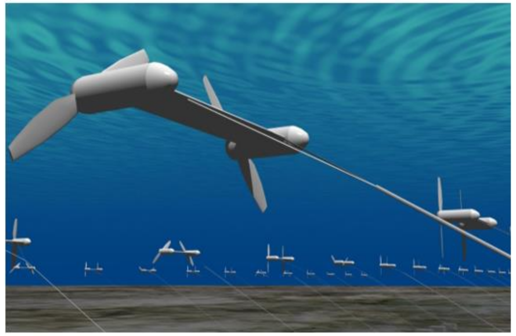


About the Control and Optimization for Renewables and Energy Efficiency (CORE) Lab - Applications…

We are leveraging advanced control techniques to revolutionize energy harvesting and efficiency **in the air, underwater, and on the ground**

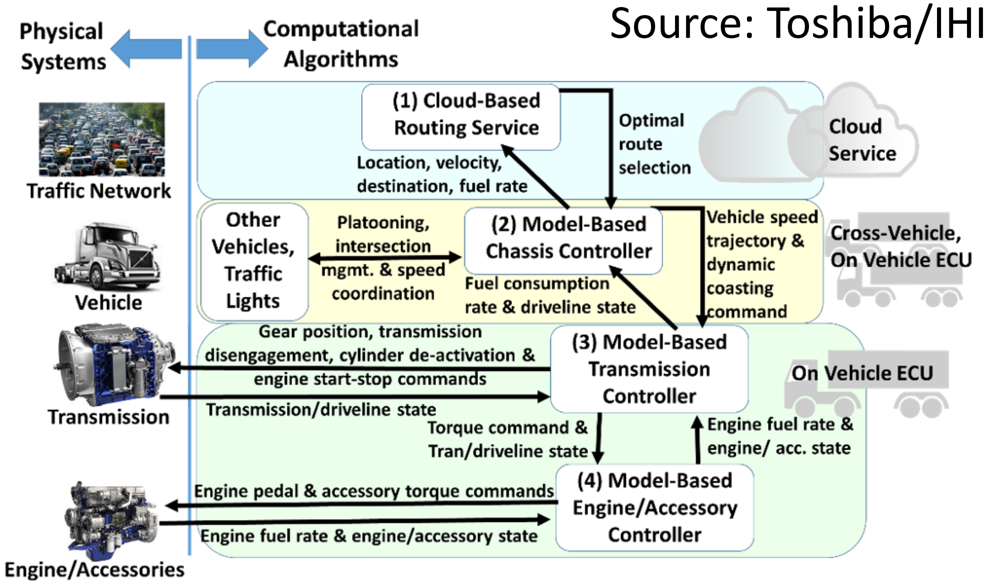
Tethered **wind and marine hydrokinetic energy systems**

- Airborne wind energy systems
- Tethered ocean current turbines (energy-harvesting AUVs)



Source: Toshiba/IHI

Maximizing fuel economy through **connected and autonomous vehicles**

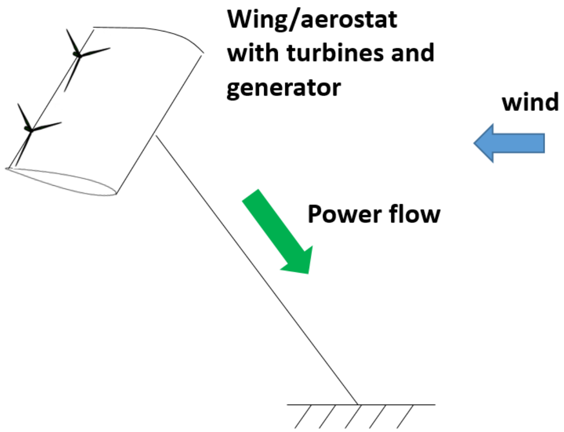


What are airborne wind energy (AWE) systems?

Fundamental characteristics:

- Replace towers with tether(s) and lifting body
- Offer increased power through altitude variation, crosswind motion, or both

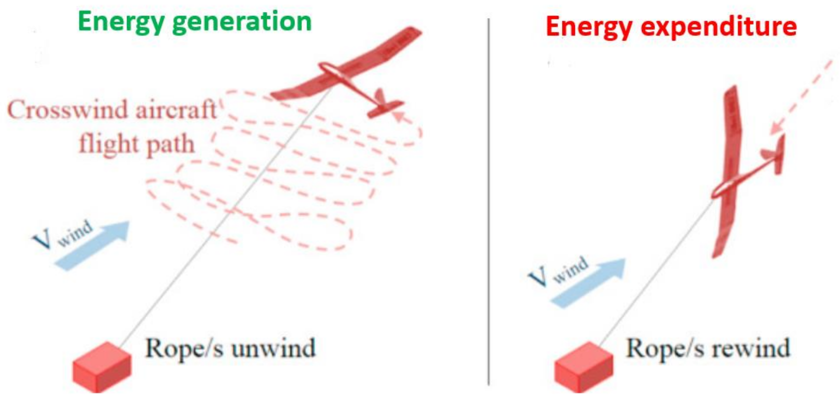
Airborne generation:



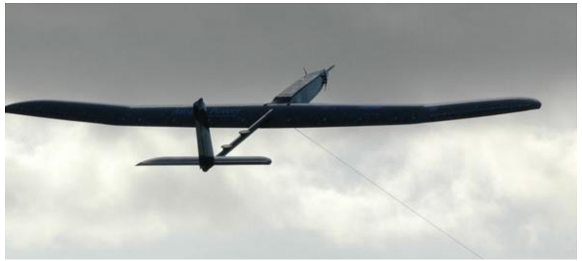
Source: Altaeros Energies, Inc.

Source: Alphabet (Makani Power)

Ground-based generation:



Source: Windlift, Inc. (previous prototype)

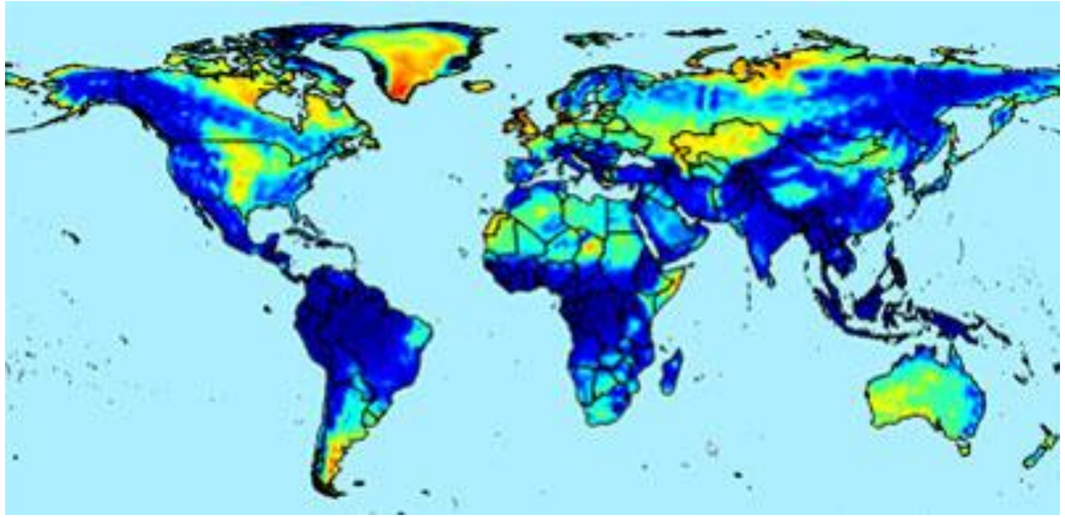


Source: Ampyx

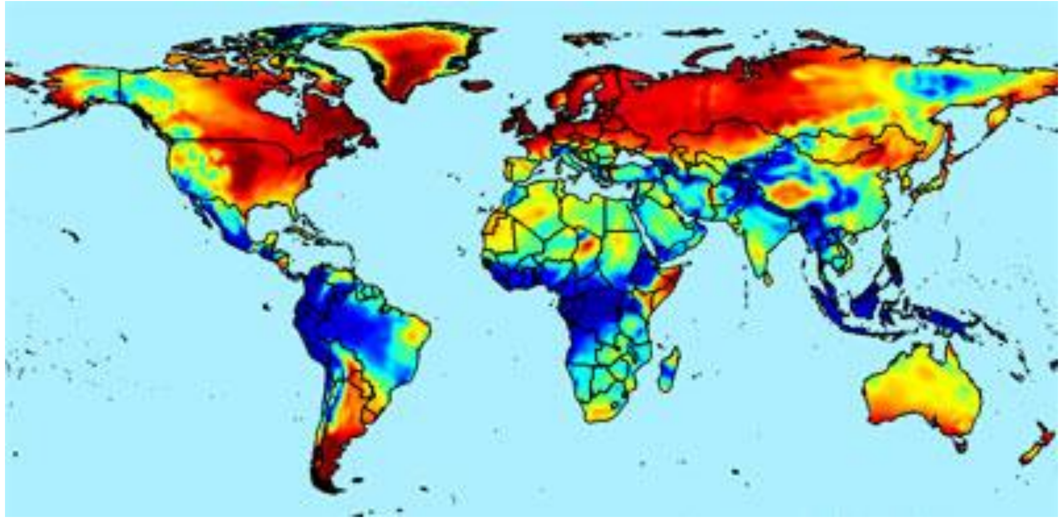
Why airborne wind?

- 5-10x power density at high altitudes
- 90+ percent material reduction vs. towers
- Can adjust altitude and motion in real time to maximize power output
- Markets: Remote off-grid/microgrid ($0.15-0.20/kWh LCOE vs. $0.50/kWh+ for diesel fuel) and deep water offshore

350 ft Altitude



2,000 ft Altitude



Average power density in kW/m²

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

Source: Joby Power (now part of Makani)

Critical challenges with AWE systems

- Replacement of towers with tethers results in a coupled system design ***and*** flight control challenge

Why co-design is important

- Simulation tools alone are not adequate for design optimization
- Full-scale experimental validation is expensive

Why legacy approaches are insufficient

To address these challenges, we have created a lab-scale co-design platform for AWE systems

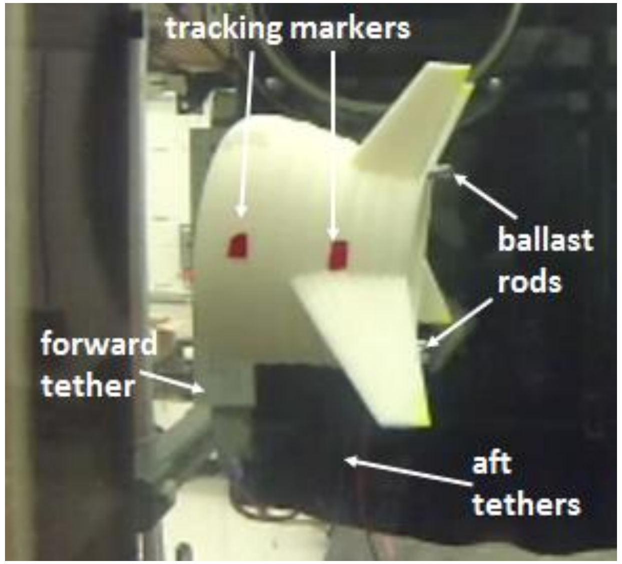
Follow-on questions:

- How can we optimally fuse (relatively) expensive experiments with cheap numerical simulations in optimizing a design?
- How can we leverage the ability to adjust control parameters during an experiment in optimizing a design?

A Lab-Scale, Water Channel-Based Platform for Closed-Loop AWE System Co-Design

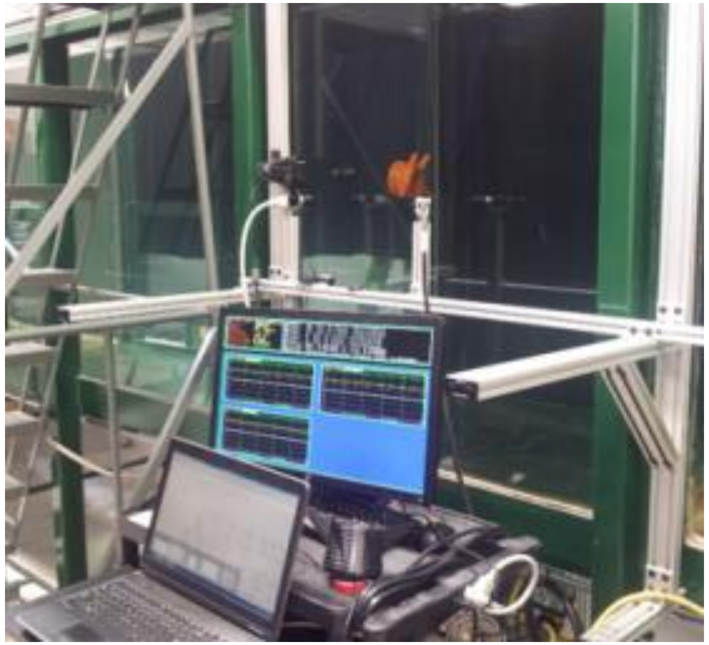
2012-2013: Passive system in the University of Michigan 2ft x 2ft Aerospace Engineering Water Channel

- 3D printed (FDM) ~1/100-scale ABS plastic models
- Rapid reconfiguration of mass distribution and tether attachments
- Non-real-time image processing
- No closed-loop control

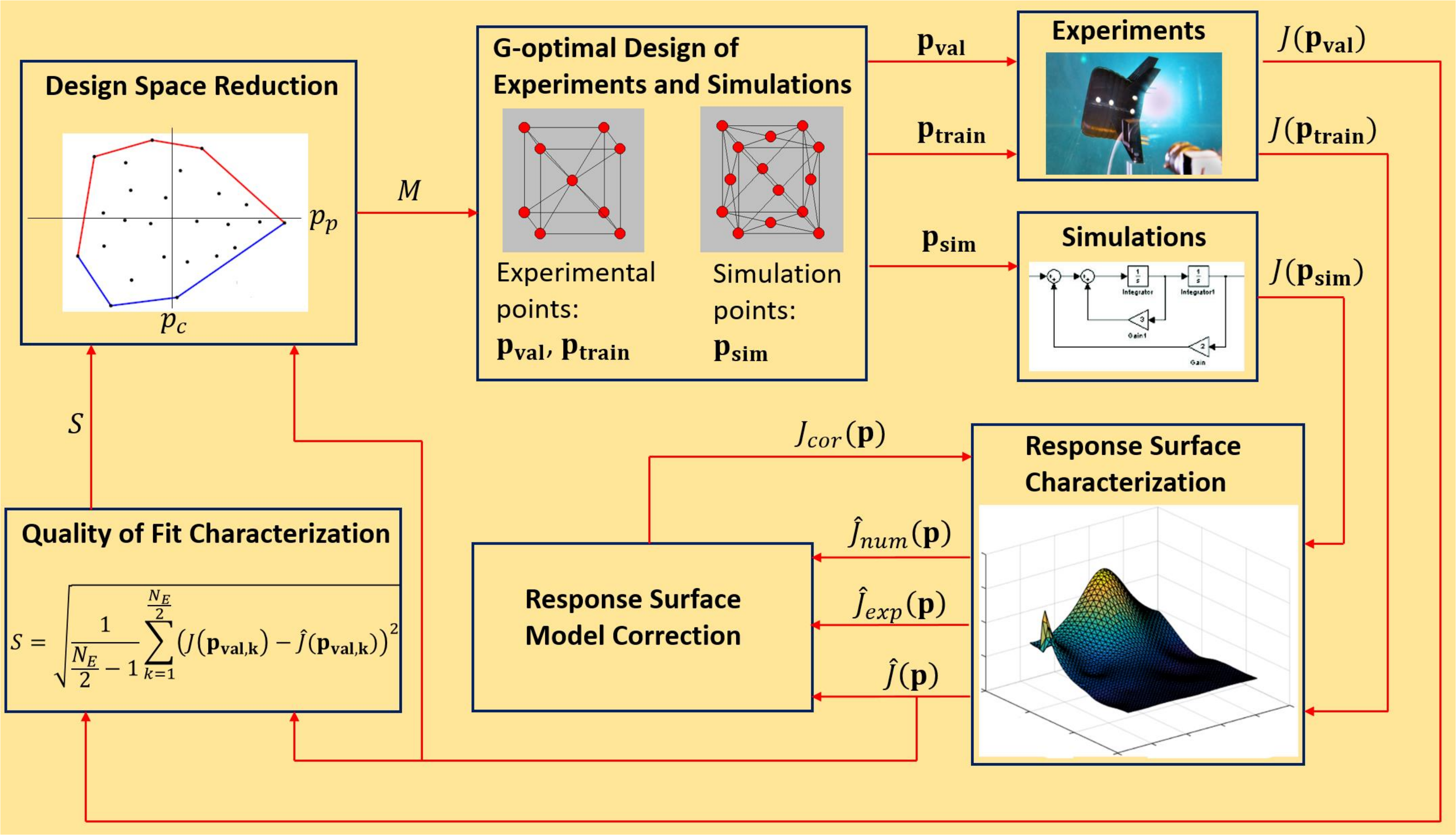


2014-present (continually evolving) active system in the UNC-Charlotte (soon to be NC State) 1m x 1m Water Channel:

- 3D printed (SLA) ~1/100-scale photopolymer resin models
- Rapid reconfiguration of mass distribution, tether attachments, and fin geometries
- Real-time image processing and closed-loop control



Formally fusing experiments with numerical tools in co-design



Key notation:

$\mathbf{p}_{val}$ = parameters used for validation experiments

$\mathbf{p}_{train}$ = parameters used for training experiments

$\mathbf{p}_{sim}$ = parameters used for Simulations

$J(\mathbf{p})$ = objective function

$\hat{J}(\mathbf{p})$ = estimated value of the objective function (i.e., the ***response surface*** output)

$J_{cor}(\mathbf{p})$ = objective function correction

S = quality of fit

M = design space

Case study in experimentally-infused plant/controller optimization

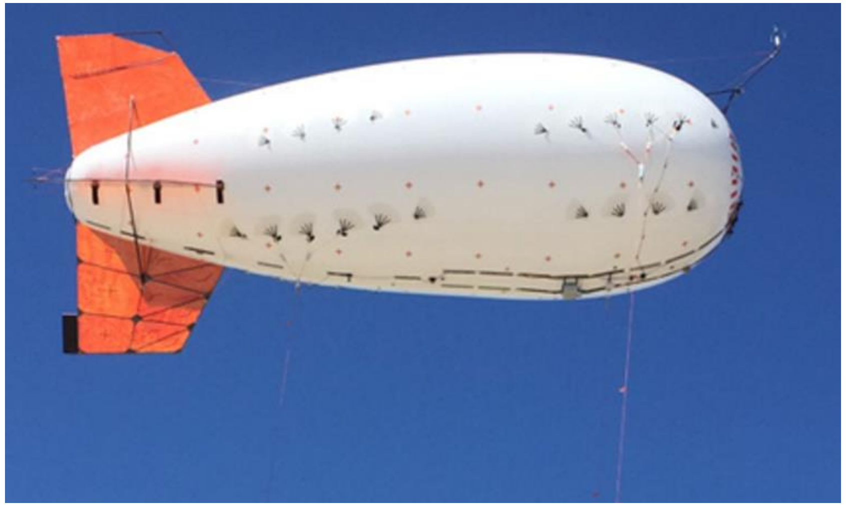
Target system: The Altaeros Buoyant Airborne Turbine (BAT)

- Two purposes: Energy generation and telecommunications
- To serve the first purpose, the BAT must remain substantially stationary, both in position and attitude
- Key plant design variables: Center of mass location, stabilizer surface areas
- Key controller variable: Pitch angle setpoint

Image credits: Altaeros Energies, Inc.

2012 BAT

2013 BAT



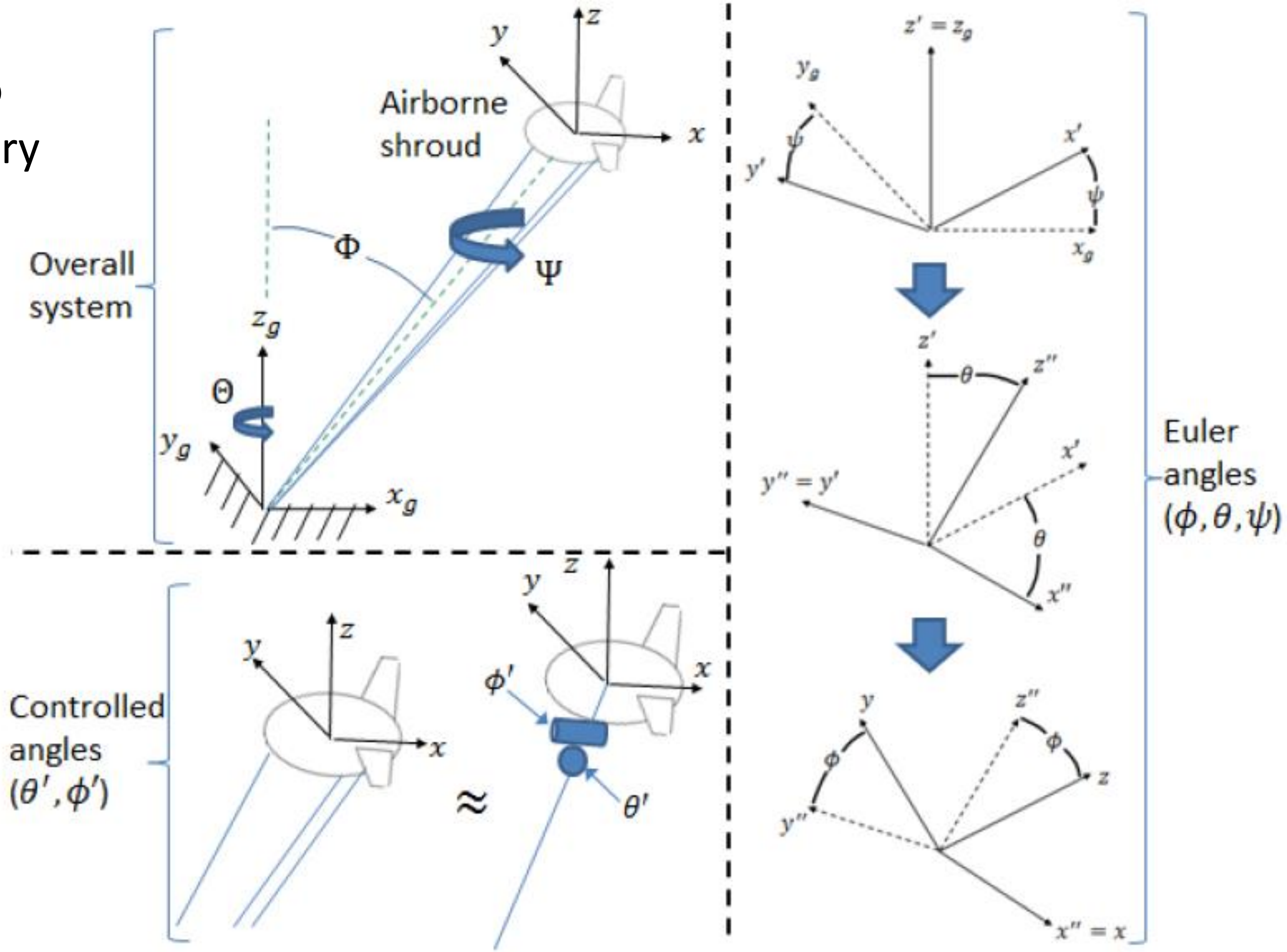
Telecommunications-only “Supertower”

A case study: Performance index

Goal: Maintain stationary flight in the presence of environmental disturbances so that it is possible to simultaneously produce energy and provide ancillary services (e.g., telecommunications)

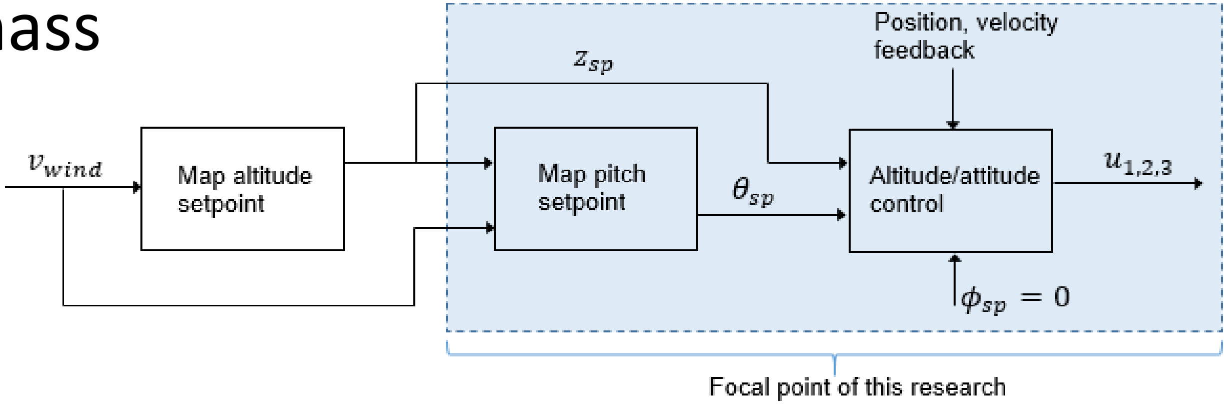
$$J = \left[\int_{T_i}^{T_f} \left(k_1(\psi - \psi_{flow})^2 + k_2(\theta_e)^2 + k_3(\phi_e)^2 + k_4(z_e)^2 + k_5(u^T u) + k_6(\Phi)^2 \right) \mathrm{d}t \right] + k_7(x_{cm} - x_{cb})^2 (T_f - T_i)$$

- Heading error: $k_1(\psi - \psi_{flow})^2$
- Roll/pitch/altitude tracking error: $k_2(\theta_e)^2 + k_3(\phi_e)^2 + k_4(z_e)^2$
- Control energy required: $k_5(u^T u)$
- Ground footprint: $k_6(\Phi)^2$
- Center of mass/ buoyancy separation: $k_7(x_{cm} - x_{cb})^2 (T_f - T_i)$



A case study: Parameters to optimize and environmental perturbation profile

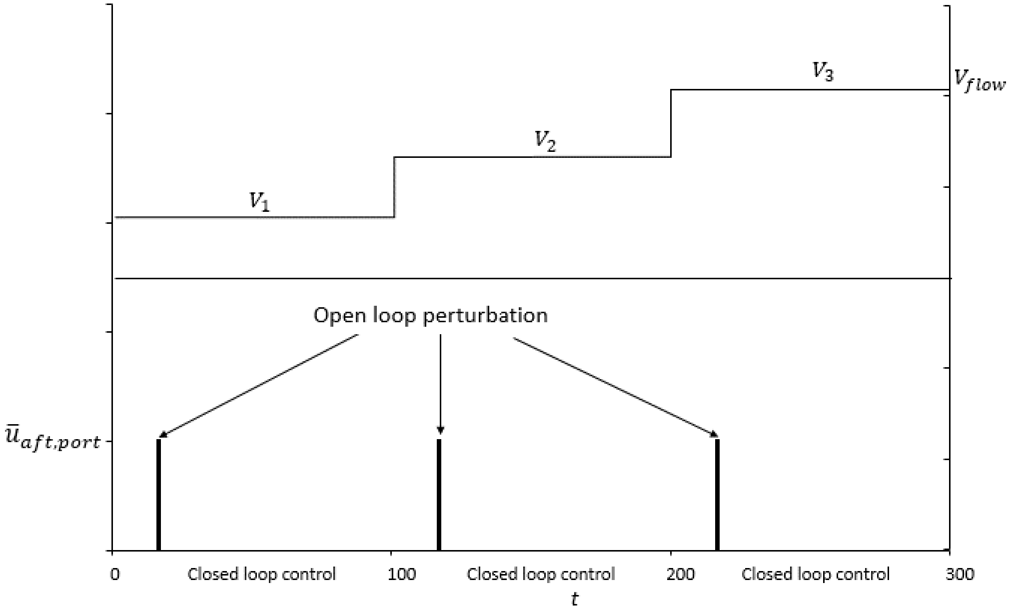
Plant parameters: Normalized center of mass location (CM_{CB}^{x}), horizontal stabilizer area (A^{H}), vertical stabilizer area (A^{V})



Control parameter: Trim pitch angle, θ_{sp}

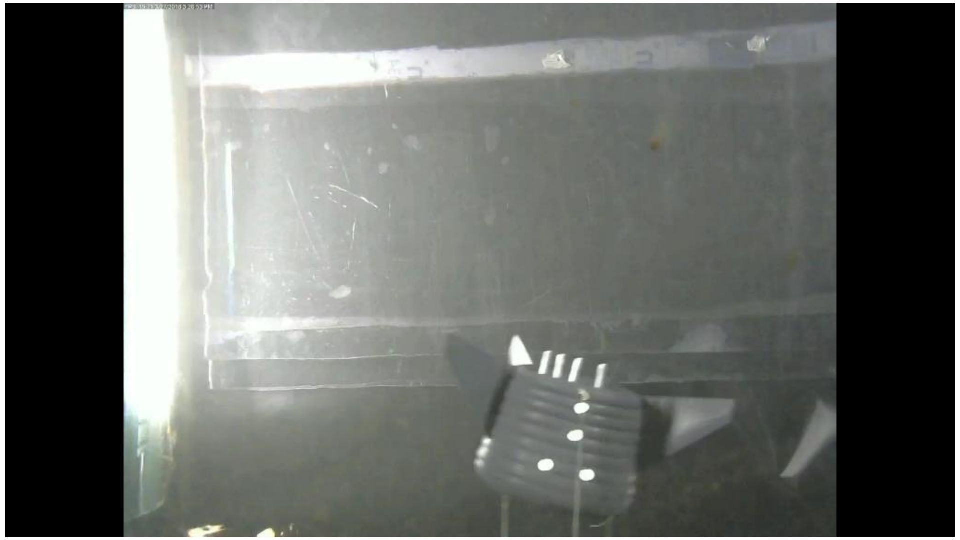
Two types of perturbations considered:

- Flow speed variations: $v_1 = 0.205\frac{m}{s}, v_2 = 0.245\frac{m}{s}, v_3 = 0.285\frac{m}{s}$
- Open-loop lateral perturbations:
  - Pull in aft port tether at full speed for 1s
  - Pause controller for 2s

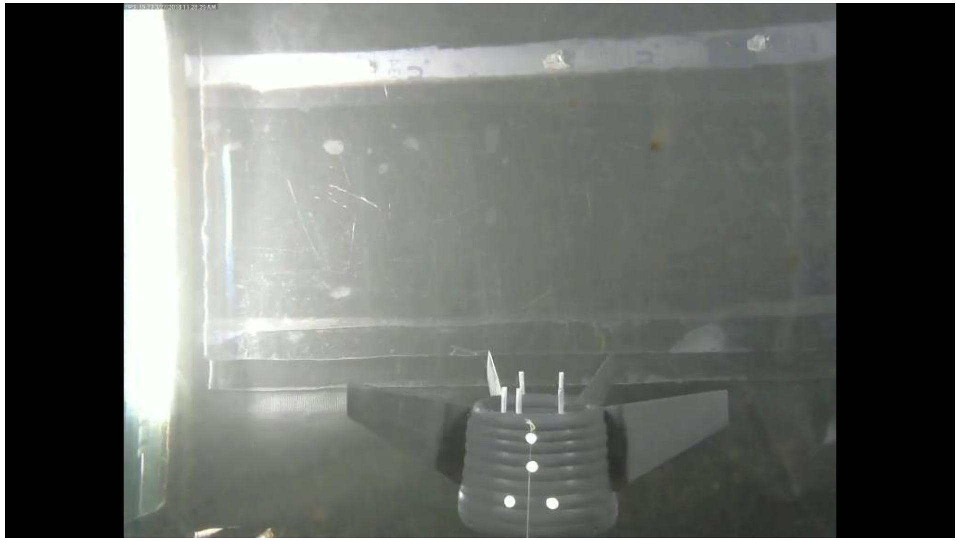


Case study: Dynamic behavior

Optimal configuration based on numerical model alone:



Optimal configuration after experimentally infused optimization:



Some observations about experimentally infused co-design

Advantages:

- Formally fuses expensive (and/or time consuming) experiments with cheap, less accurate simulations
- Methodically explores the entirety of the (reduced) design space at each iterations

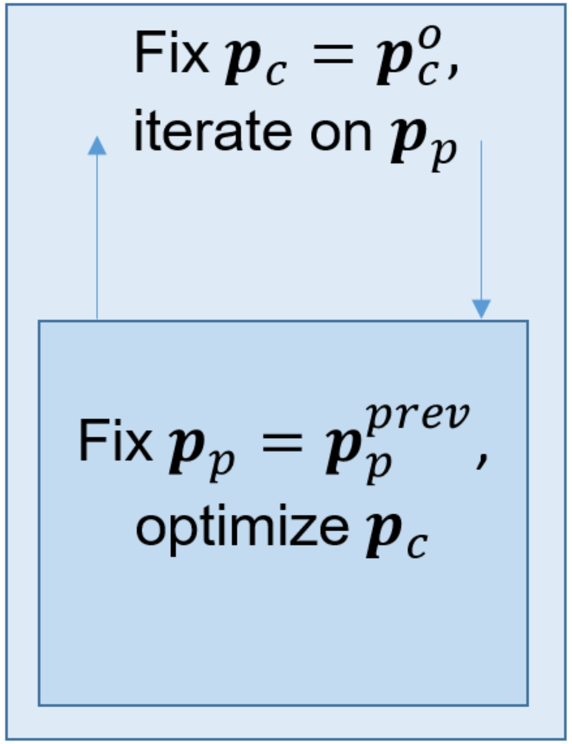
Limitations:

- Plant and control design parameters are not treated fundamentally differently
- Actual experiments have only focused on two parameters (2-model simulations on 4 parameters)

To address these limitations, can we leverage the fact that control design parameters can be adjusted <u>during</u> experiments, whereas plant design parameters need to be adjusted <u>between</u> experiments?

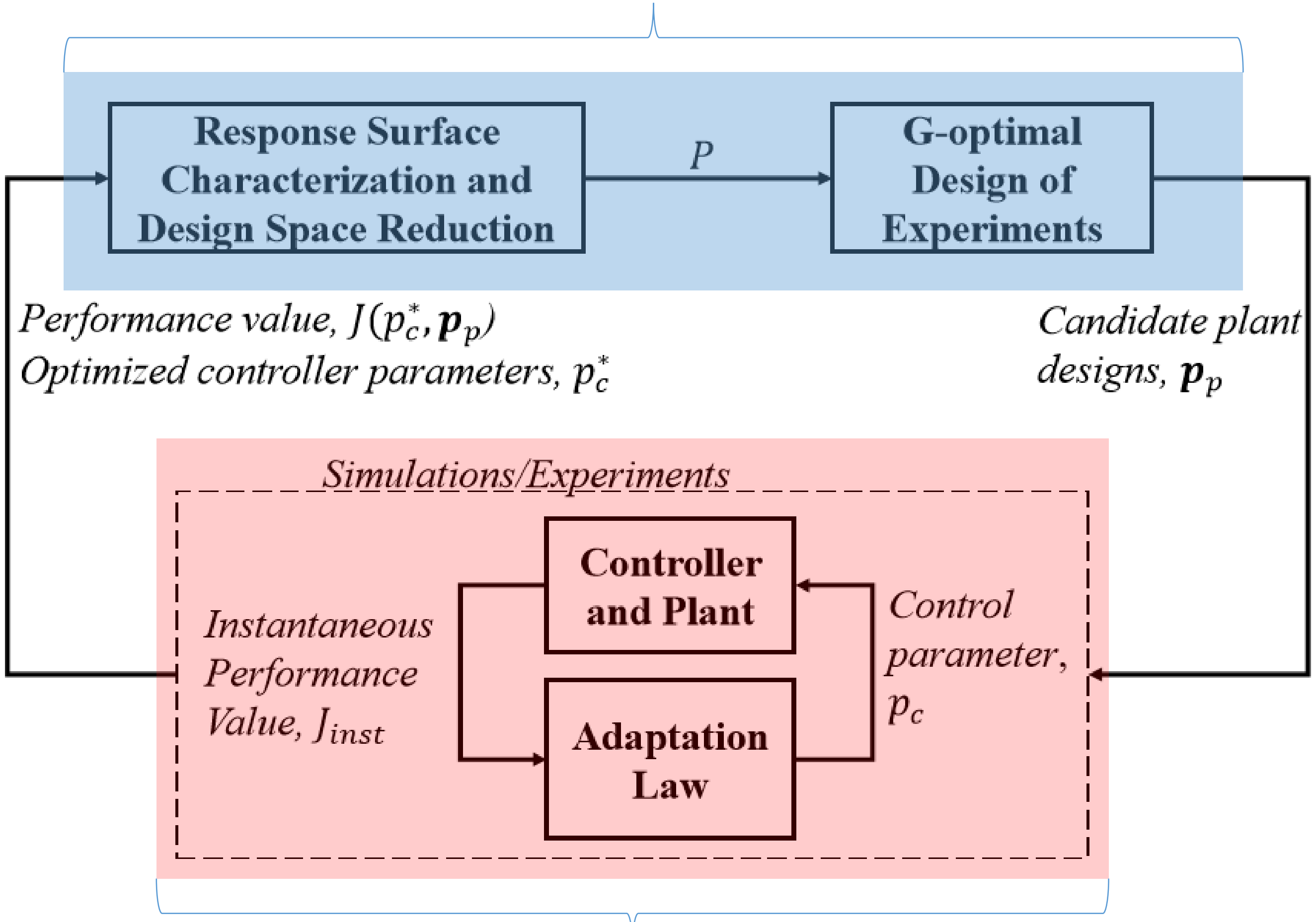
Nested experimental co-design – an introduction

Nested framework (reminder):



Our nested experimental co-design framework:

Same tools as earlier – plant design parameters only



Control design optimization ***during*** experiments/simulations (**new**!)

Case study – Initial simulation-based results

Design parameters:

- x_{cm}: Longitudinal center of mass location (plant)
- k_s: Stabilizer area scale factor (plant) – Each stabilizer area given by $A_s = k_s A_{nom}$
- θ_{sp}: Trim pitch angle (controller)

Performance index: *Main goal – Reduce variations in heading angle (ψ), roll angle (ϕ), and Zenith ("blowdown") angle (Φ)*

$$J = \int_{T_i}^{T_f} \left[k_\psi \psi(t) + k_\phi \phi(t) + k_\Phi \Phi(t) \right] dt$$

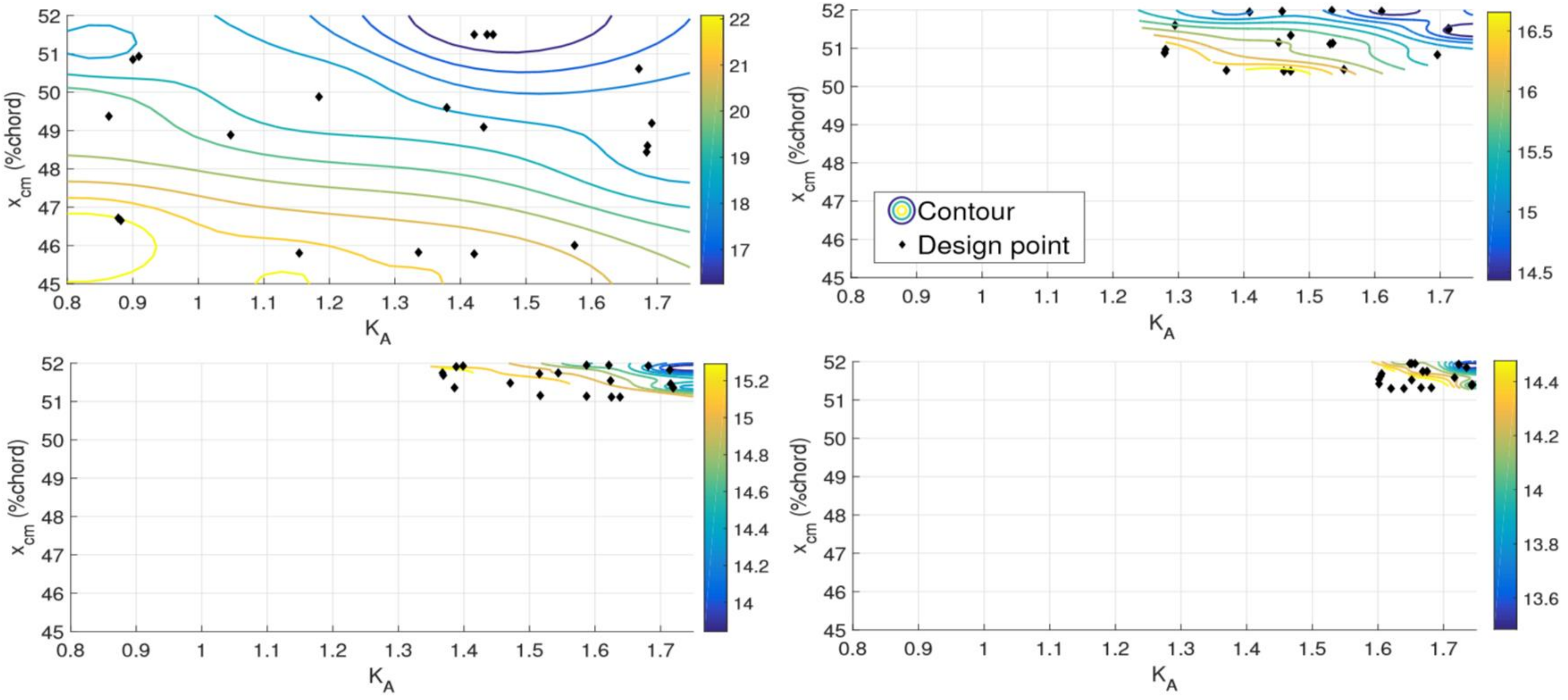
Continuous environmental perturbation profile:

- *Key point:* Because we are continually adjusting the controller design parameter(s), we need to excite the system with a *consistent* perturbation profile

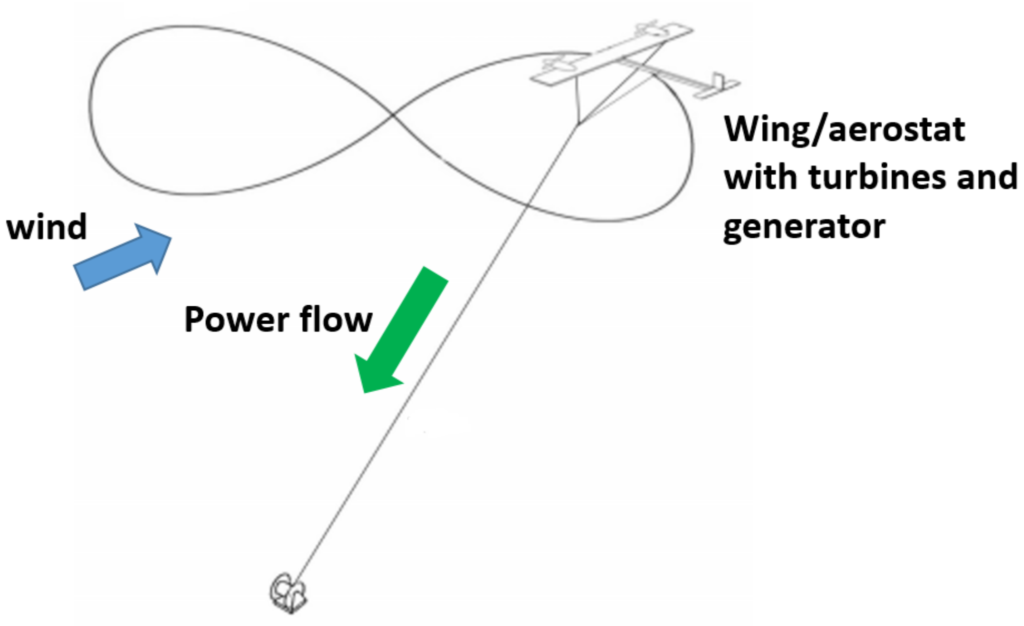
$$v_x = v_{base} + v_{x0} \sin\left(\omega_{dist} t + \frac{\pi}{2}\right) \qquad v_y = v_{y0} \sin(\omega_{dist} t) \qquad v_z = v_{z0} \sin\left(\omega_{dist} t + \frac{\pi}{2}\right)$$

Case study – Initial simulation-based results

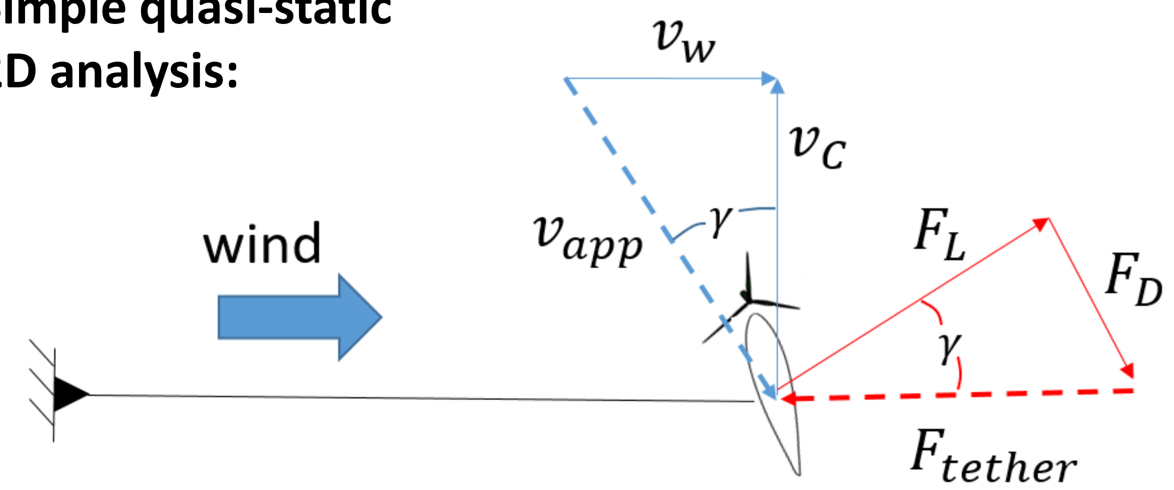
Design space reduction:



Moving forward: Co-design for power-augmenting crosswind flight



Simple quasi-static 2D analysis:



Key point: High (or even moderate) lift/drag ratios can lead to theoretically huge power augmentation

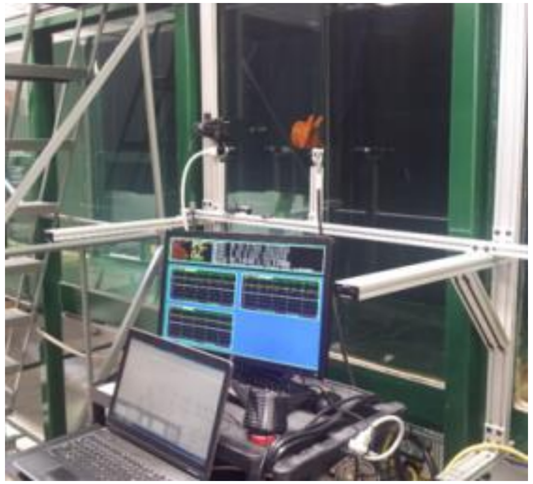
- Flying perpendicular to the wind (figure-8 patterns or circles) increases the apparent wind speed, v_{app}
- Instantaneous power production is proportional to v_{app}^3
- **Plant** design challenge: Developing a stable airborne system that maximizes lift/drag
- **Control** design challenge: Optimizing crosswind path parameters under variable wind profiles

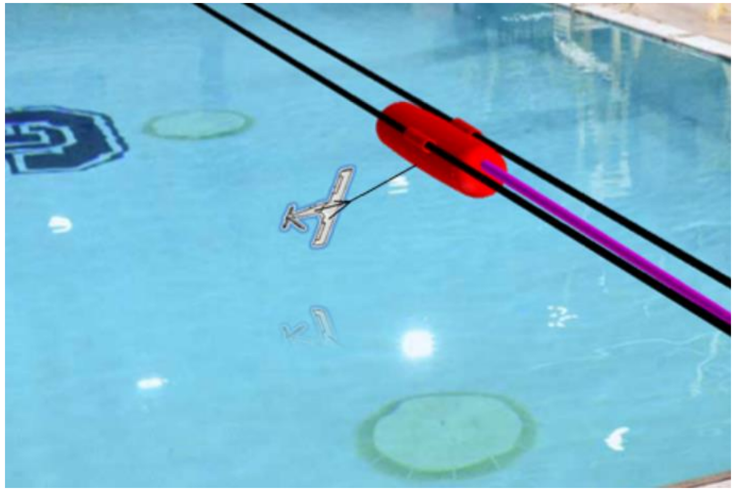
Moving forward: Multi-scale experimentally infused co-design

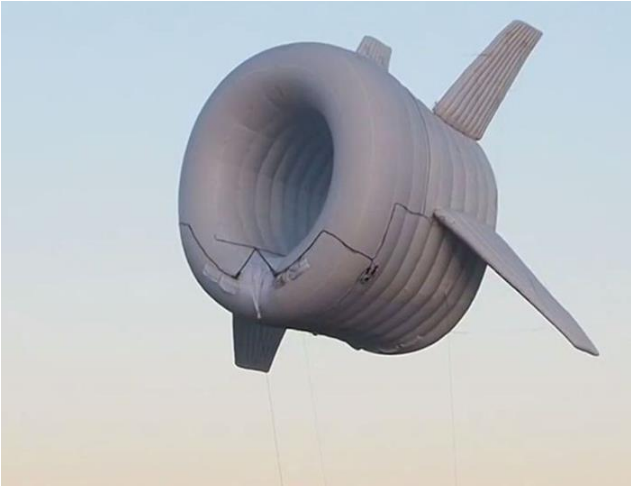
Main idea: Formally fuse numerical/analytical models with experiments at multiple scales (e.g., lab-scale and full-scale)

- Often, not all dynamic characteristics can be captured at lab scale (example: 3D printed water channel models **characterize flight dynamics** but are **not power producing**)
- Significant costs associated with full-scale testing

Example of a multi-scale framework for tethered energy systems:
Water channel -> pool tow testing -> full-scale flight testing



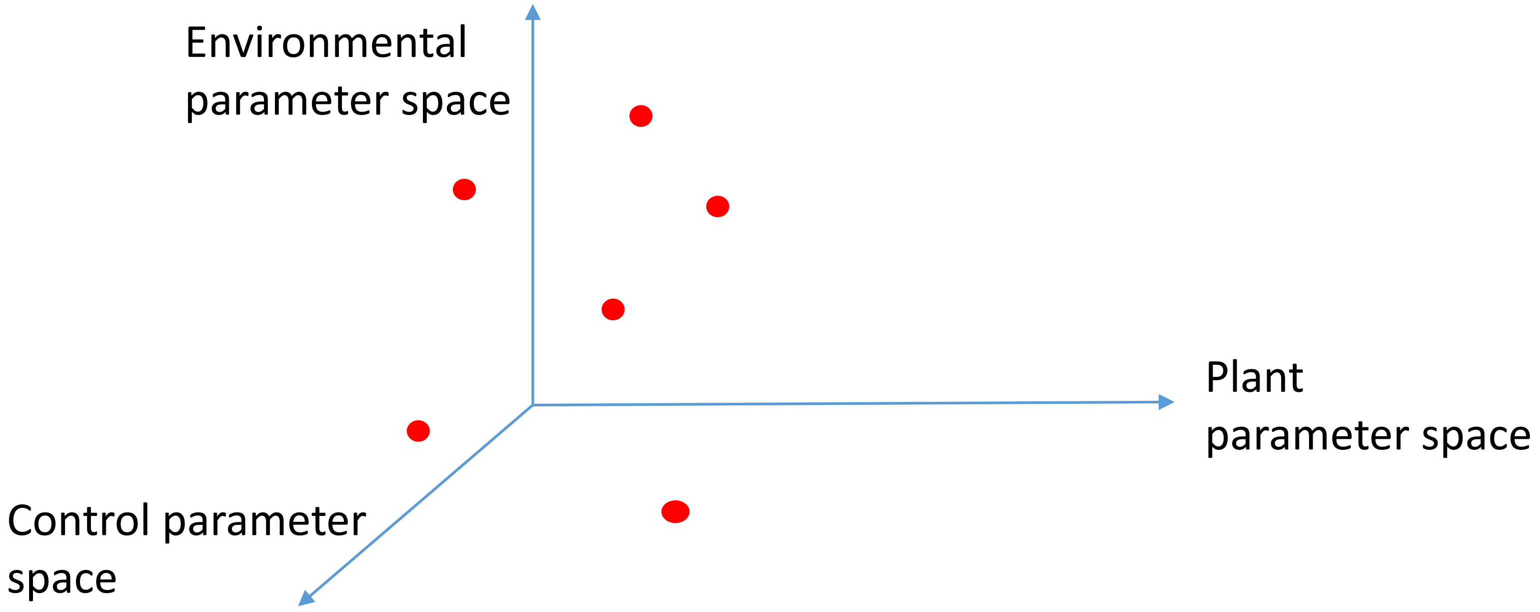




Moving forward: Robust co-design with respect to environmental disturbance profiles

Presently, experimental co-design relies on a prescribed, deterministic environmental disturbance profile

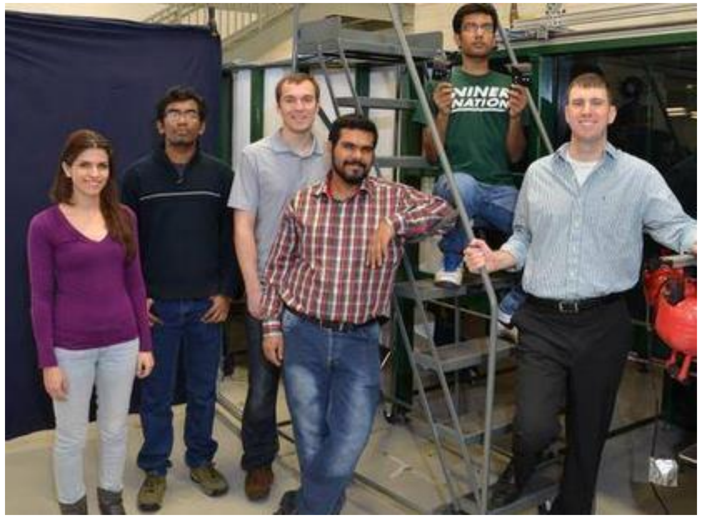
Idea: Perform design of experiments over the combined design and disturbance space



Challenge: ***<u>Huge</u>*** environmental disturbance space must be parameterized compactly to limit the required number of experiments

Acknowledgements

Students:



Pictured (left -> right):

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