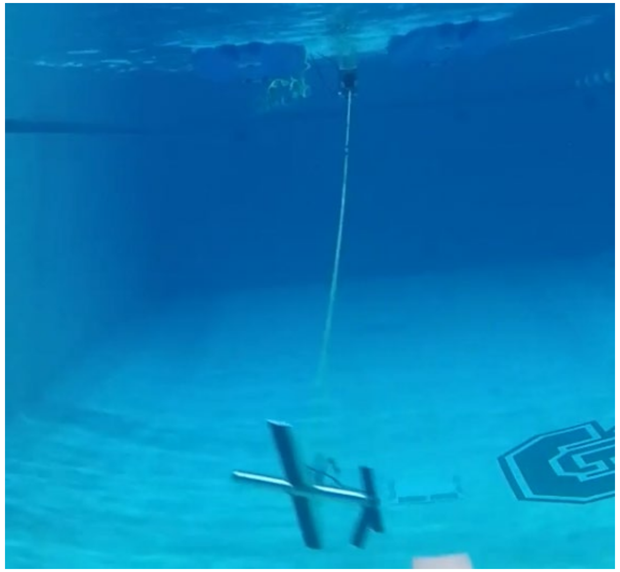
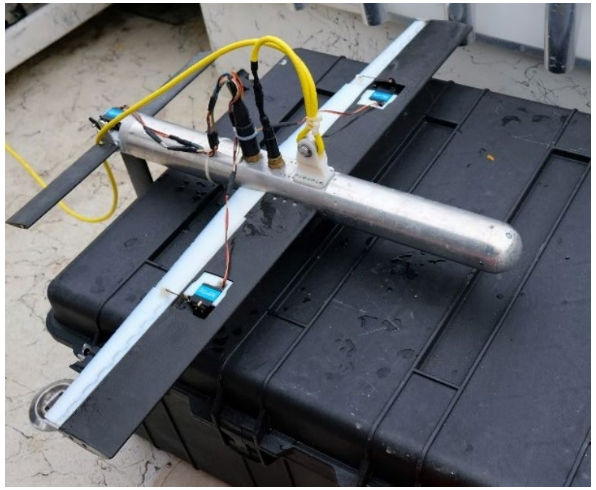
# DE-EE0008635 – Device Design and Robust Periodic Motion Control of an Ocean Kite System for Marine Hydrokinetic Energy Harvesting





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North Carolina State University

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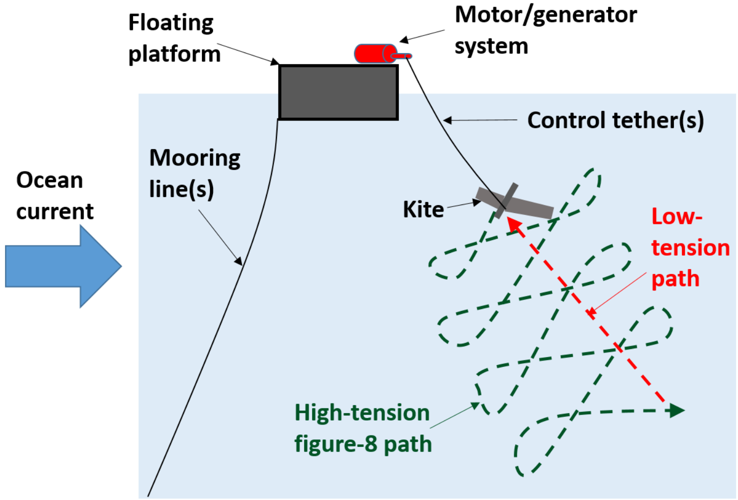
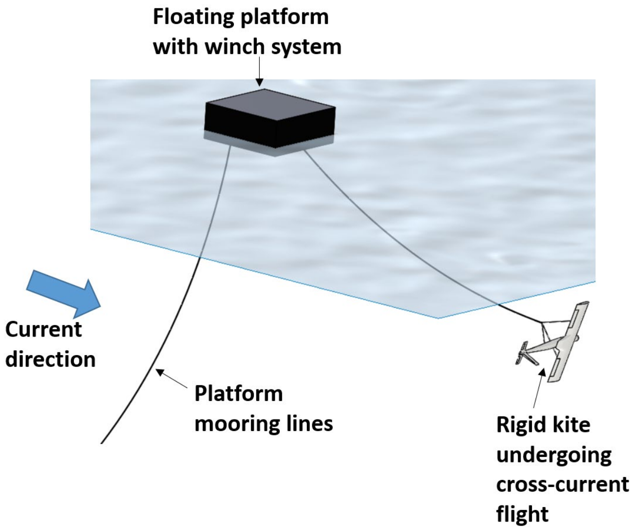
Wednesday, July 20, 2022

# Project Overview (Graphical)

## The concept:

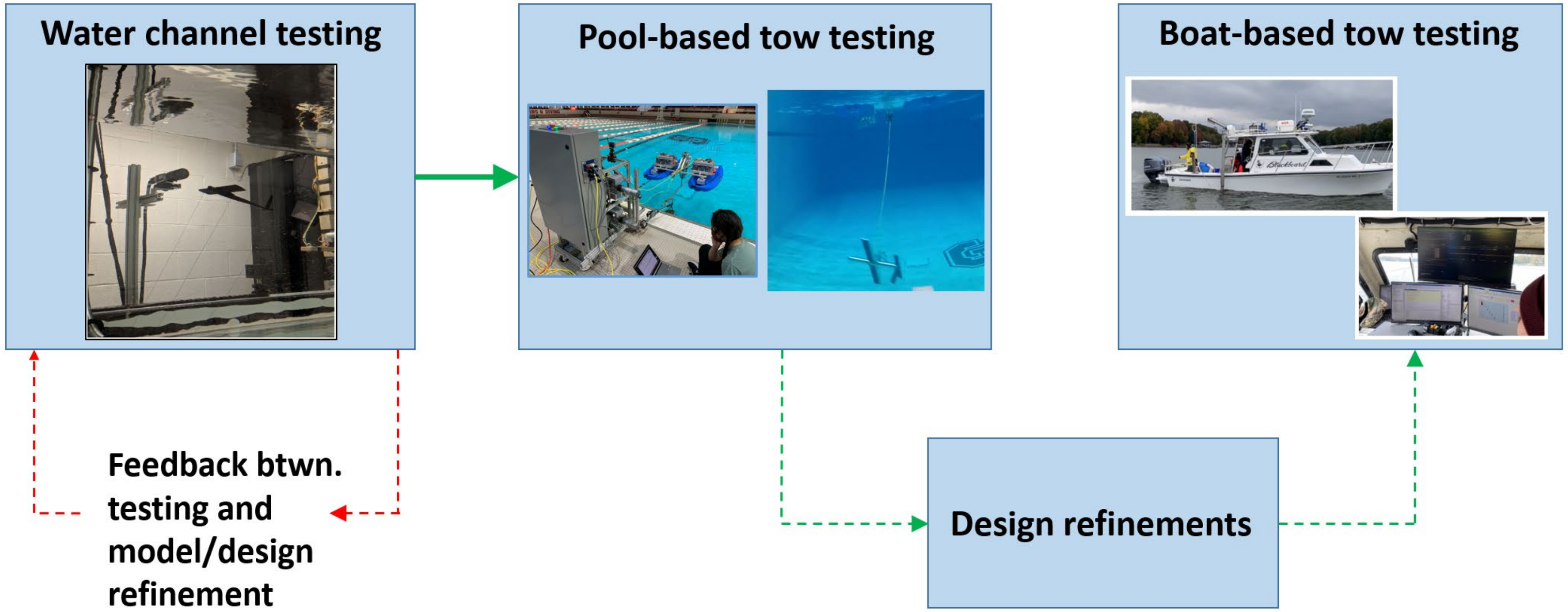
*Cyclic* operation demands *periodic* optimal control.




## The experimental validation process:

*Progressive experimental prototyping enables early risk reduction.*



# Project Overview

## Project Summary

- ***Overarching goal:*** Develop a kite design, open-source optimal control strategy, and open-source modeling tools for winch-based power generation.
- ***Research need:*** Kites can yield an order of magnitude greater power/mass than stationary tidal and current devices, yet open-source kite design/control research was previously absent in the U.S. MHK R&D portfolio
- ***Unique features:*** All modeling and control results are open-source and experimentally validated at 3 scales – water channel, pool, and open water

## Intended Outcomes

- ***Expected outcome 1***: Experimentally validated underwater kite dynamic model
- ***Expected outcome 2***: Optimal control algorithms for cyclic flight path and spooling profile optimization
- ***Expected outcome 3***: Open-water validation of optimal control algorithms
- ***Expected outcome 4***: Development of a U.S. Blue Economy technology-to-market pipeline for underwater kites

## Project Information

**Principal Investigator(s)**

Chris Vermillion (NC State University)

**Project Partners/Subs**

- Co-PIs at NC State (Kenneth Granlund, Andre Mazzoleni)
- University of Maryland (Hosam Fathy)
- North Carolina Coastal Studies Institute (Michael Muglia)
- Florida Atlantic University (Gabriel Alsenas, Bill Baxley)

**Project Status**

Ongoing

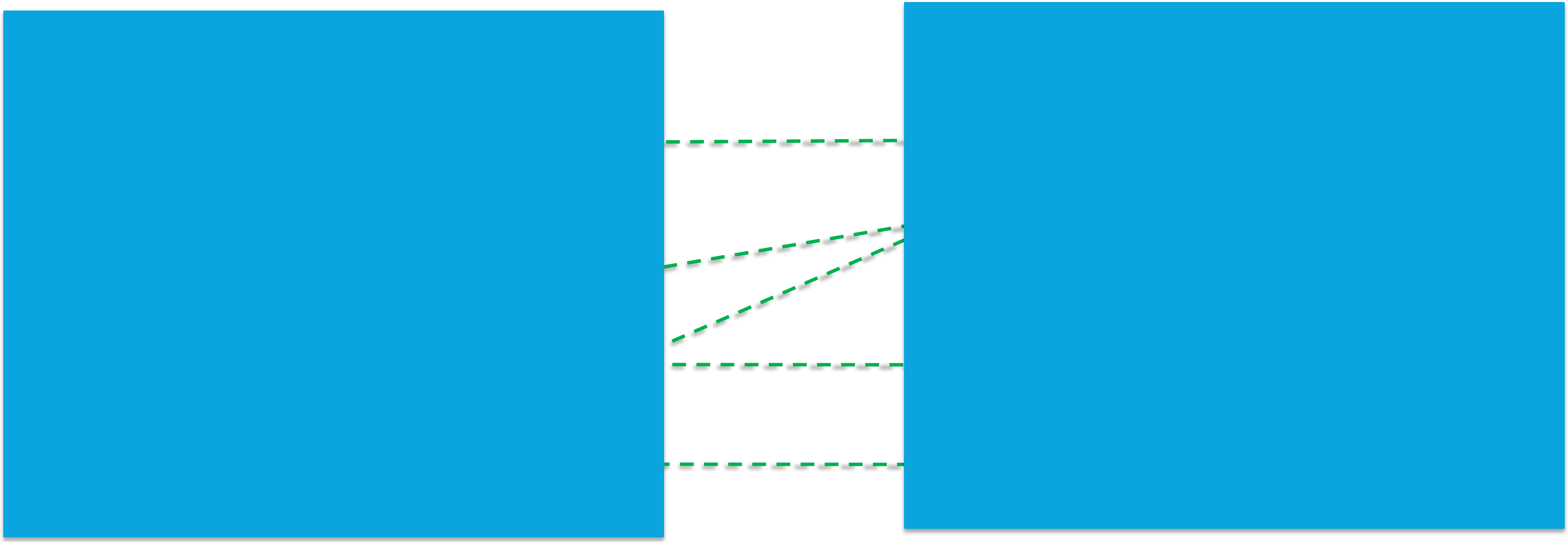
**Project Duration**

- Start date: May 1, 2019
- End date: October 31, 2022

**Total Costed (FY19–FY21)**

$1,596,279

# Project Objectives: Relevance

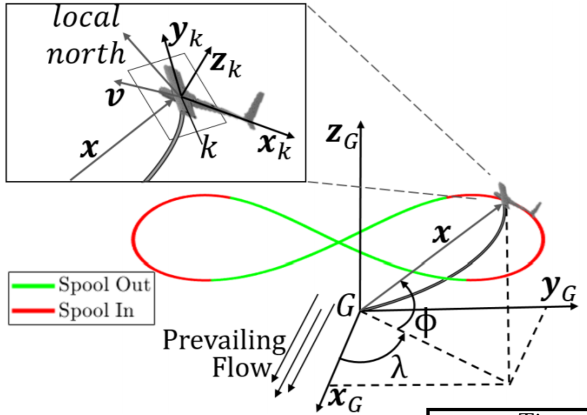


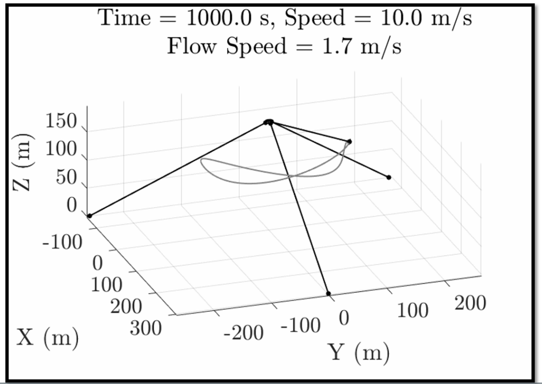
# Project Objectives: Approach

## Dynamic model development:

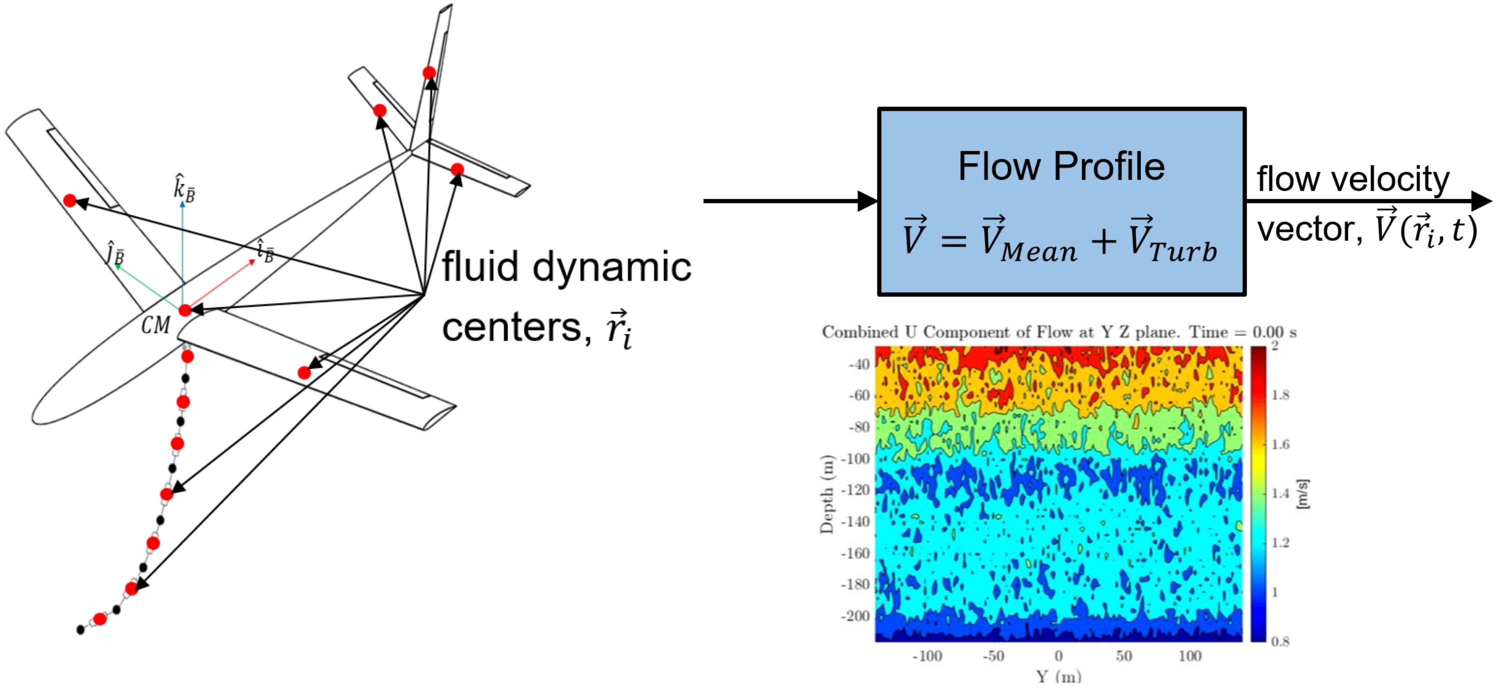
**Key takeaway:** The dynamic model fuses a (i) 6 degree-of-freedom kite dynamics model, (ii) multi-link tether model, (iii) optional floating platform model, and (iv) environmental model into a single Simulink-based open-source framework.

### Coordinate system (top) and floating platform setup (bottom):



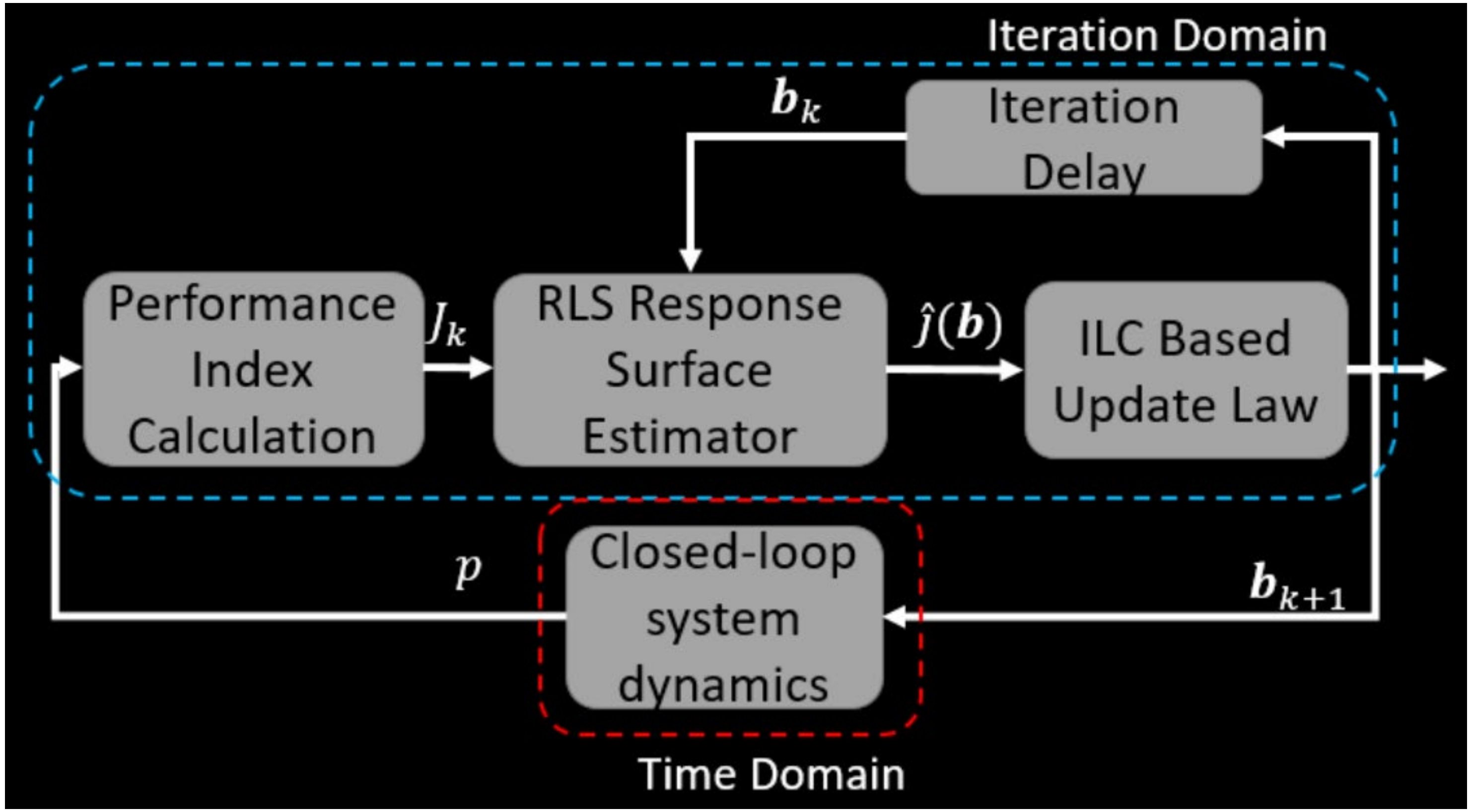




### Integration of kite, tether, and flow model:



# Project Objectives: Approach

## Economic iterative learning control (ILC) for cyclic path and spooling optimization:




$\boldsymbol{b_k}$ = Flight control "basis" parameters at cycle *k*

$J$ = Economic performance index (cycle-averaged power)

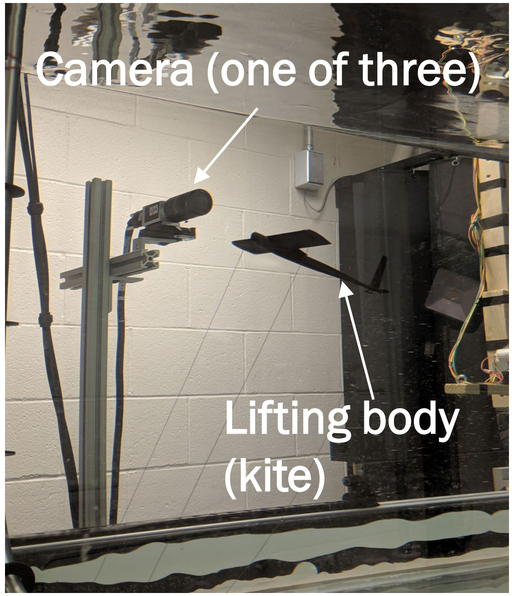
$\boldsymbol{p}$ = Vector of available measured variables

**Key takeaway:** ILC is used to update key flight control parameters from one spool-out/spool-in cycle to the next, in order to maximize an "economic" metric (lap-averaged power).

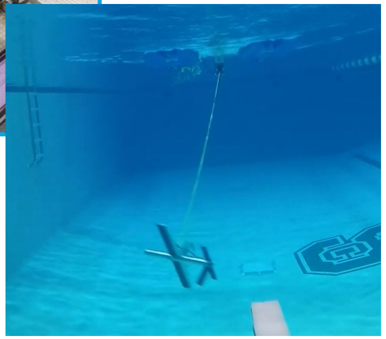
# Project Objectives: Approach

## Progressive experimental validation:

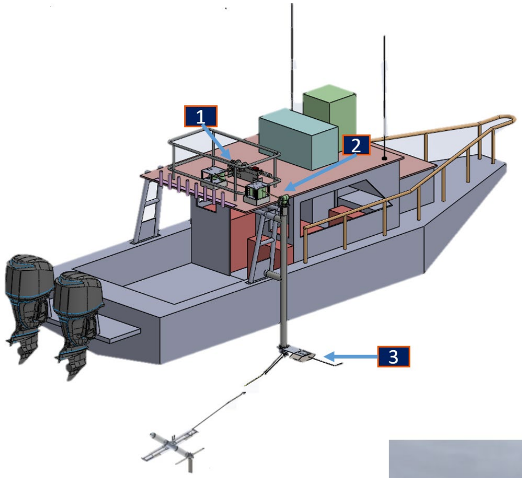
Water channel testing
(~10cm wingspan, 2019-2020):




NCSU pool tow testing (~1m
wingspan, 25-yard tow length, 2021):

Open-water tow testing in Lake Norman
(~1m wingspan, 5-mile fetch, 2021-2022):




Key takeaways:

- Water channel platform used to **validate the dynamic model**
- Pool testing platform used to **validate the closed-loop tracking controller**
- Open-water platform used to **validate iterative learning and periodic optimal control approaches**

# Project Objectives: Expected Outputs and Intended Outcomes

## Expected Outputs:

- Validated, open-source kite dynamic model
- Validated, open-source iterative learning controllers for cyclic path and spooling optimization
- Dissemination through 10+ publications
- Invention disclosures for key IP
- At least one follow-on project utilizing kite technology (e.g., powering observational equipment, powering an autonomous underwater vehicle)

## Expected Outcomes:

- Increased ease of developing underwater kite technology in the U.S. (due to open-source models and controllers)
- Closed-loop control performance benchmarks for kite-based energy systems
- Increased engagement of industry and national labs in underwater kite development

# Project Timeline

## FY 2019

Q2: Project start

Q3: Fully implemented kite + tether dynamic model

## FY 2020

Q2: Demonstration of non-adaptive/non-optimal control performance

Q3: Demonstration of control performance improvement under ILC

Q4: Water channel-based experimental validation

Go/no-go: Demonstration of techno-economic potential based on developed/validated modeling tools

## FY 2021

Q1: Experimental kite and pool-based tow mechanism fabrication

Q2: Initial pool-based tow tests

Q3: Complete pool-based tow tests

Q4: Prep for FY 2022 open-water tests

# Project Budget

| Total Project Budget – Award Information | | |
|---|---|---|
| DOE | Cost-share | Total |
| $1,894,654 | $473,882 | $2,368,536 |

| FY19 | FY20 | FY21 | Total Actual Costs FY19–FY21 |
|---|---|---|---|
| Costed | Costed | Costed | Total Costed |
| $135,949 | $597,037 | $863,293 | $1,596,279 |

- Expenditures through present total $1,904,612
- No-cost extension granted through October 31, 2022 (will enable investigation into enhanced PTO/winch designs and further tech-to-market pipeline development)
- All originally budgeted costs are expected to be spent by the end of this no-cost extension
- The team has received follow-on funding (>$3M) from Martin Defense Group (via the DARPA Manta Ray program) to develop kites for powering autonomous underwater vehicles

# End-User Engagement and Dissemination

- Stakeholder group 1: Blue Economy kite technology adopters
  - Entered into >$3M contract with Martin Defense Group to develop a kite for powering an autonomous underwater vehicle (AUV)
  - Actively seeking other DoD opportunities and Minesto collaborations for early-stage underwater kite adoption
- Stakeholder group 2: National laboratories (e.g., NREL, Sandia)
  - PI Vermillion went on a “wild west dissemination tour” in May, 2022 to NREL and Sandia
  - NREL is contemplating collaborative work to further develop kite dynamic modeling tools
- Stakeholder group 3: Academic research labs
  - Research has been widely disseminated through over 20 peer-reviewed publications
  - Simultaneously, invention disclosures (and one provisional patent to-date) have been filed to protect key IP prior to publication

# Performance: Accomplishments and Progress (Summary)

## Outputs:

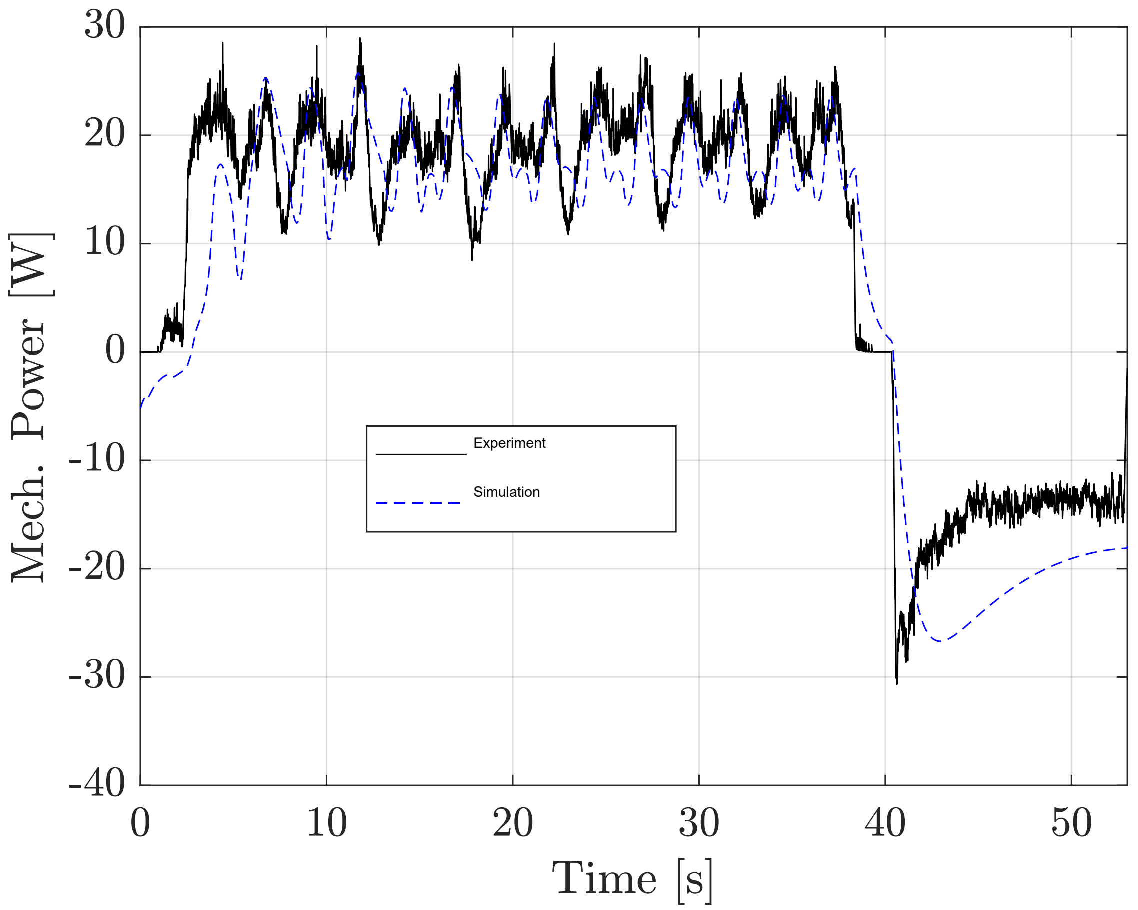
- Kite dynamic model validated against water channel, pool, and open-water data
- Iterative learning control performance evaluated in open water
- Over 20 accepted peer-reviewed publications
- 3 invention disclosures with one provisional patent so far
- Follow-on funding secured to develop kite technology to power autonomous underwater vehicles (with Martin Defense Group, via the Manta Ray program)

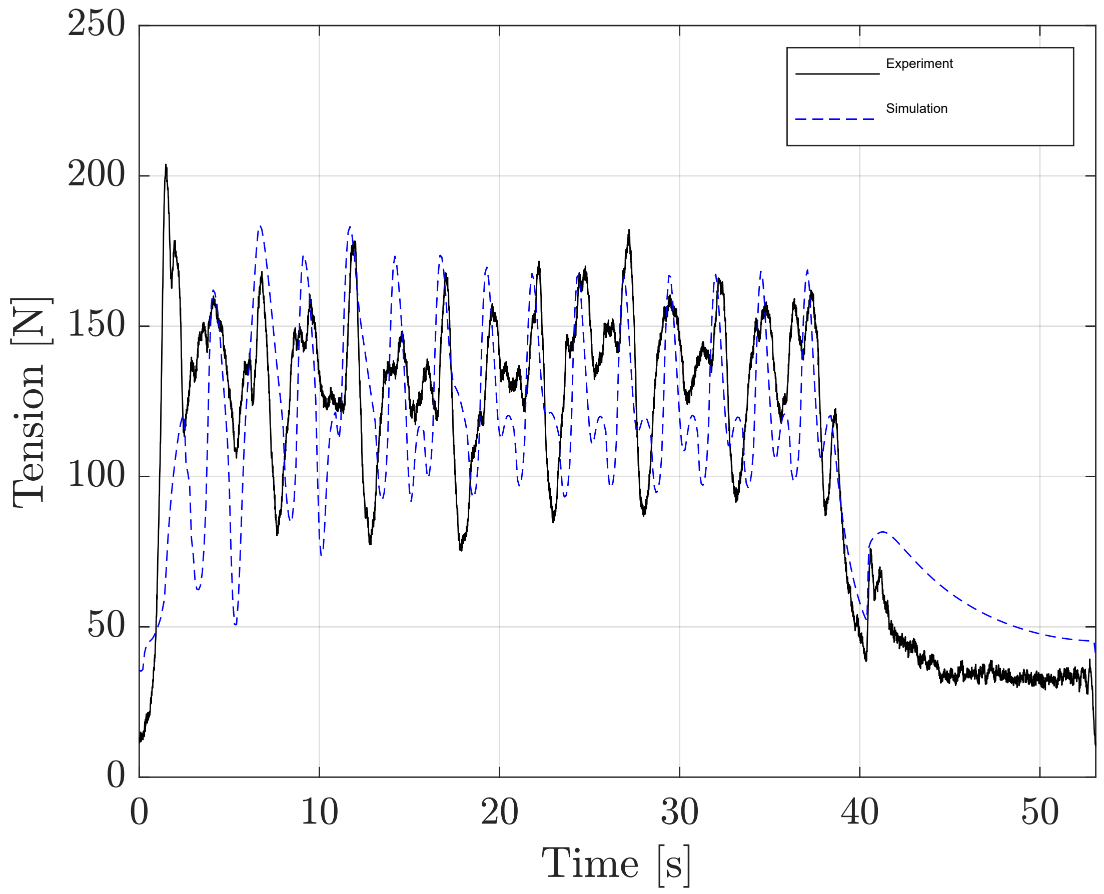
## Outcomes:

- Team's dynamic model and controllers are available worldwide
- Presently engaging with NREL regarding the formalization of kite modeling software/fusion with KiteFAST for airborne wind
- Underwater kite technology is now a highly active U.S. research area

# Performance: Accomplishments and Progress (Details)

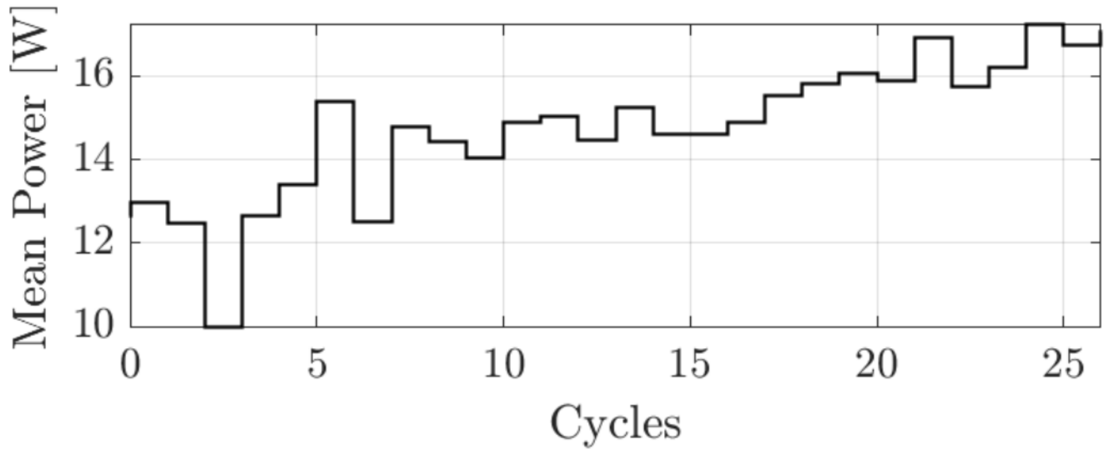
Sample scaled, open-water model validation efforts – 0.8m span kite, 1.25 m/s flow – Key takeaway: Experimental results closely match model predictions.

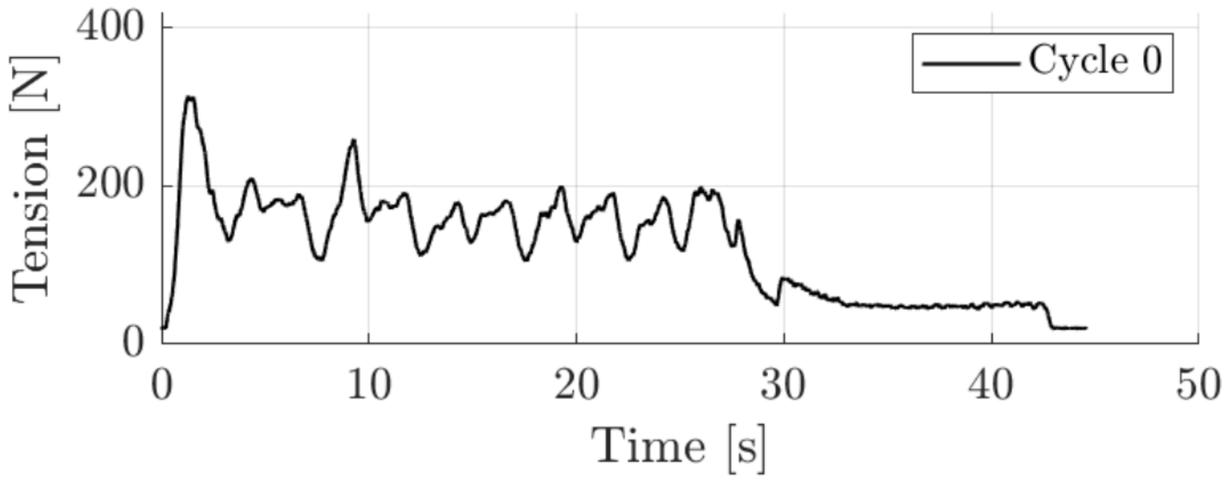


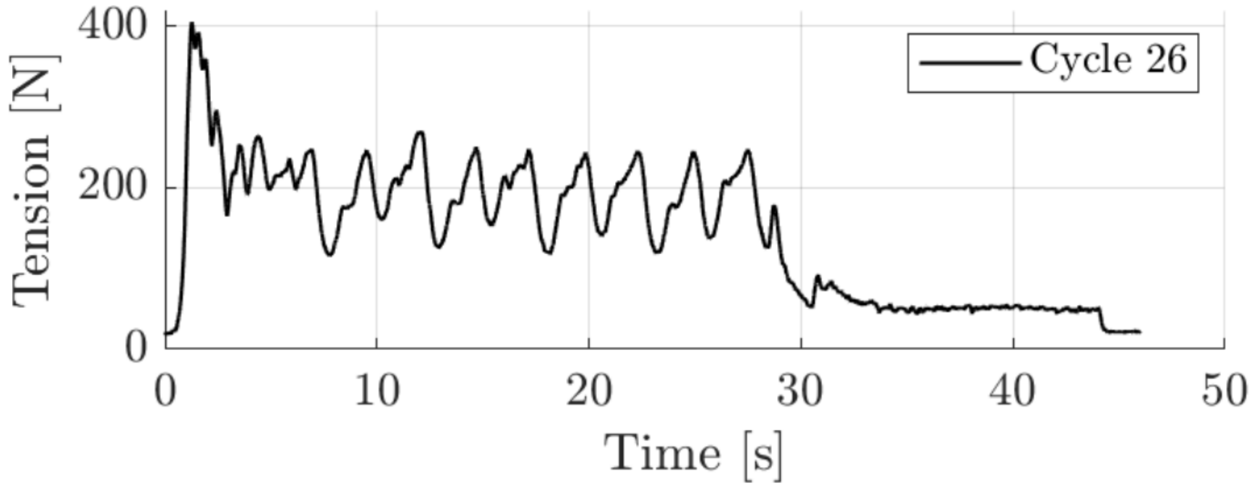



# Performance: Accomplishments and Progress (Details)

Sample scaled, open-water controller validation efforts – 0.8m span kite – Key takeaway: Iterative learning enables 30 percent performance improvement beyond manual tuning.

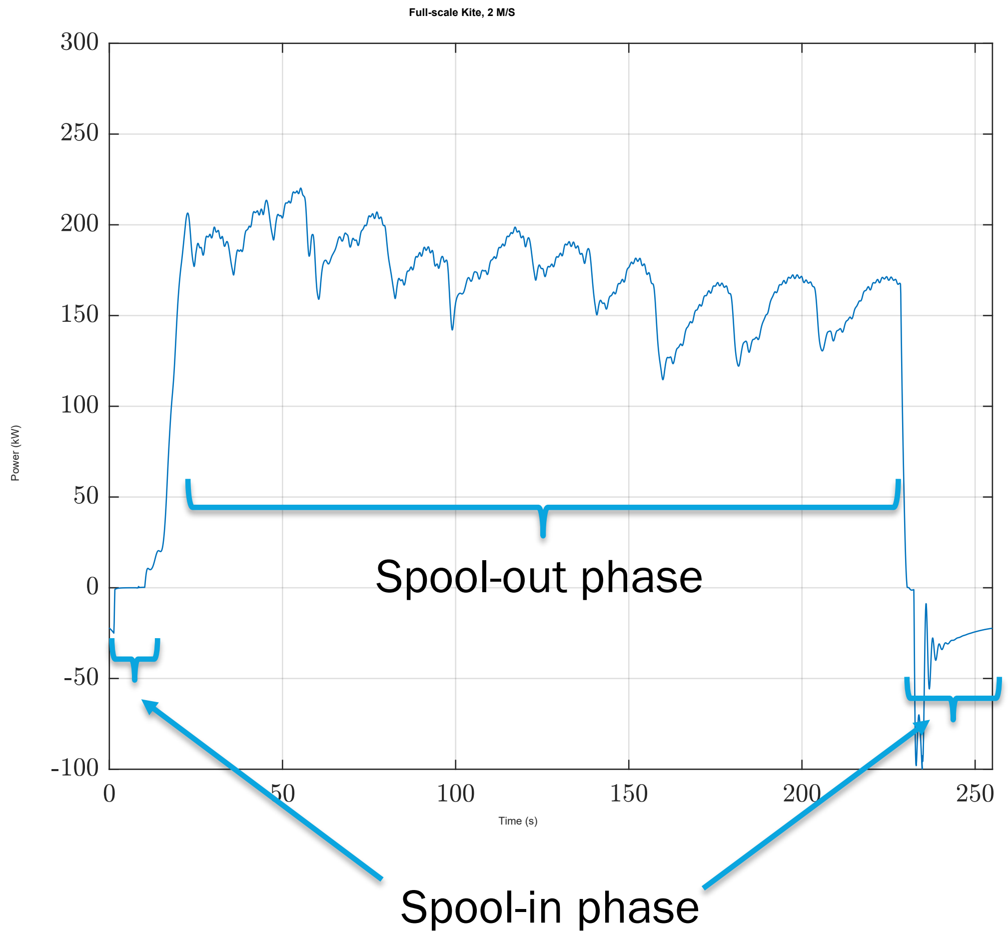


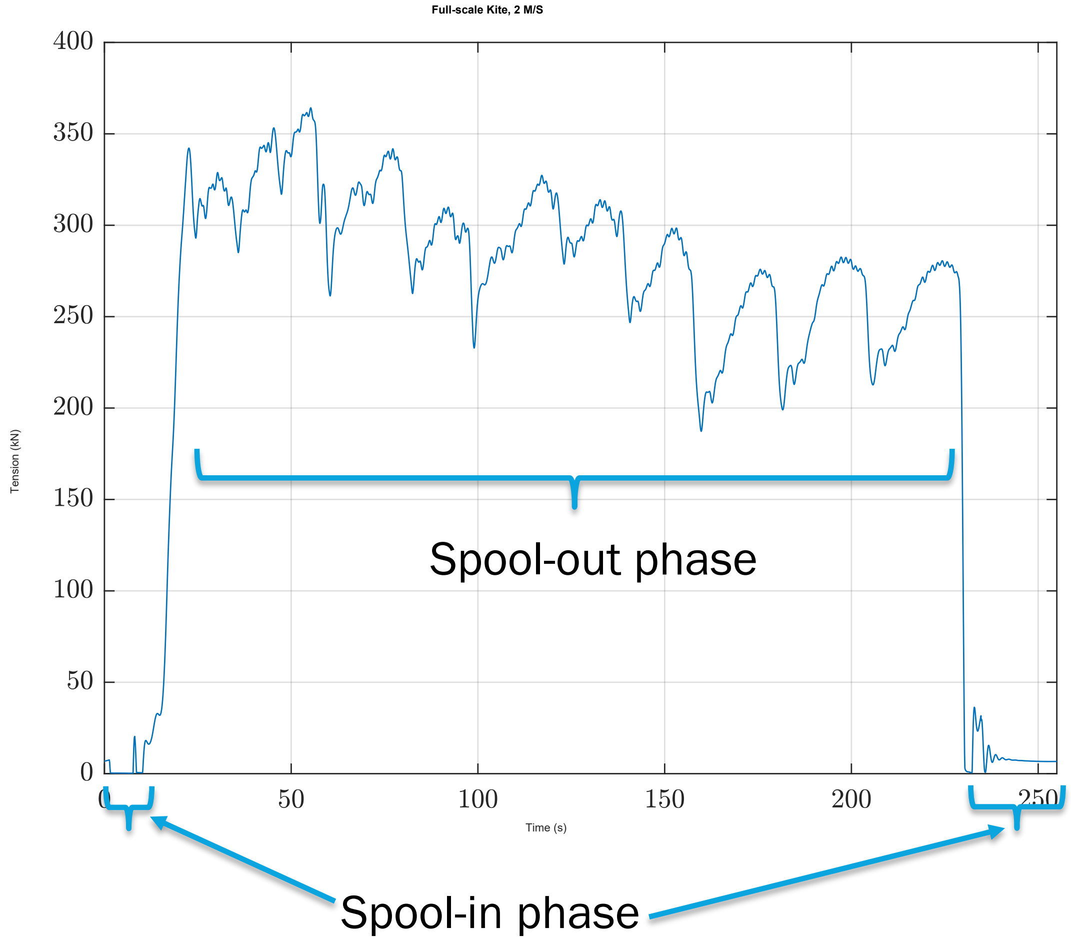



# Performance: Accomplishments and Progress (Details)

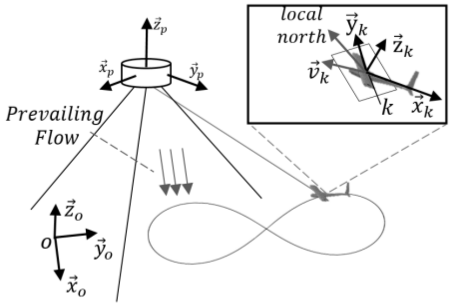
Sample full-scale performance projections – 10m span kite – <u>Key takeaway: Tens of Watts at small scale translate to 100-200kW at full scale.</u>

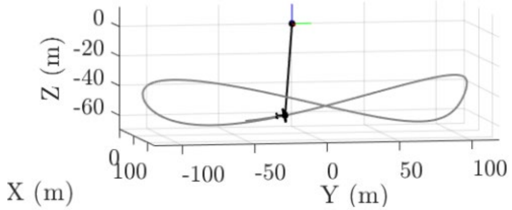


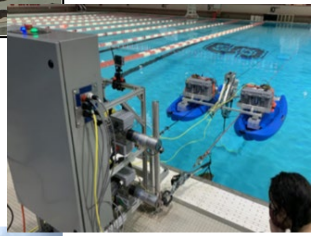
# Future Work

## Past 3 years



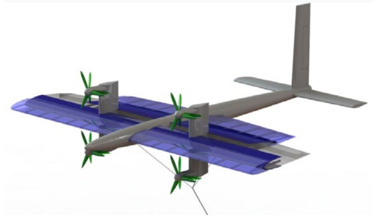

Modeling

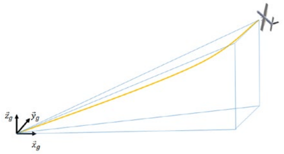


Progressively scaled experiments

## Present

## Future





Enabling foundational research:

- KiTEcon: A unified resource, dynamic, and economic tool for **ki**te **t**echno-**e**conomic assessment
- Path optimization for ultra-long tether operation
- Morphing wing designs for variable-depth operation
- High-efficiency power take-off (PTO)

MARTIN DEFENSE GROUP

Bringing the technology to market:

- Manta Ray program (Martin Defense Group) + additional DoD opportunities
- Ongoing Minesto discussions
- Seeking SBIR/STTR opportunities

# Q&A