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

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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

Key project outcomes:
• Develop an open-source, experimentally validated underwater kite (+ tether and platform) model
• Develop optimal control algorithms for cyclic path and spooling profile optimization
• Validate control algorithms in an open-water setting
• Develop a U.S. Blue Economy tech-to-market pipeline for underwater kites

Impacted program goals:
• Develop and validate numerical modeling tools
• Drive innovation in components, control, manufacturing, and materials
• Validate performance and reliability through prototype testing, including in-water testing at multiple scales
• Assess potential market opportunities, including relevant maritime markets
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:

Flow Profile
\[ \vec{v} = \vec{V}_{\text{Mean}} + \vec{V}_{\text{Turb}} \]

flow velocity vector, \( \vec{V}(\vec{r}, t) \)
Project Objectives: Approach

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

\[ b_k = \text{Flight control “basis” parameters at cycle } k \]

\[ J = \text{Economic performance index (cycle-averaged power)} \]

\[ p = \text{Vector of available measured variables} \]

**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):
- Camera (one of three)
- Lifting body (kite)

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

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

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<thead>
<tr>
<th>Expected Outputs:</th>
<th>Expected Outcomes:</th>
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<tr>
<td>• Validated, open-source kite dynamic model</td>
<td>• Increased ease of developing underwater kite technology in the U.S. (due to open-source models and controllers)</td>
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<td>• Validated, open-source iterative learning controllers for cyclic path and spooling optimization</td>
<td>• Closed-loop control performance benchmarks for kite-based energy systems</td>
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<td>• Dissemination through 10+ publications</td>
<td>• Increased engagement of industry and national labs in underwater kite development</td>
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<td>• Invention disclosures for key IP</td>
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<td>• At least one follow-on project utilizing kite technology (e.g., powering observational equipment, powering an autonomous underwater vehicle)</td>
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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

**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

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

#### Total Project Budget – Award Information

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- 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)

Outsouts:

• 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
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.
Sample full-scale performance projections – 10m span kite – **Key takeaway:** Tens of Watts at small scale translate to 100-200kW at full scale.
Future Work

Past 3 years
- Modeling

Present
- Progressively scaled experiments

Future
- Enabling foundational research:
  - KiTEcon: A unified resource, dynamic, and economic tool for kite techno-economic assessment
  - Path optimization for ultra-long tether operation
  - Morphing wing designs for variable-depth operation
  - High-efficiency power take-off (PTO)

- Bringing the technology to market:
  - Manta Ray program (Martin Defense Group) + additional DoD opportunities
  - Ongoing Minesto discussions
  - Seeking SBIR/STTR opportunities
Q&A