Optimal WEC Controls using Causal and MPC Methods
Project #: EE0007173
## Project Overview

### Project Summary

- Development & testing of universal optimal controls for WEC devices using causal and non-causal methods:
  - Universally applicable to any WEC topology
  - Allow for PTO loss model representation
  - Constrained optimal control allowing for system-level economic optimization - “Controls Co-Design”
- Worked with 3 device developers to apply controls
- Developed wave prediction system leveraging buoy networks
- Testing at sea of controls methods on 8kW point absorber

### Project Objective & Impact

- Move controls algorithms out of the lab and into WECs operating at sea (from TRL3 to TRL6)
- Enable robust Model Predictive Control (MPC) and causal control of at-sea WEC devices
- Enable wave prediction that is “good-enough” for MPC
- Enable constrained optimal control at sea, which is essential to controls co-design and to achieve techno-economic optimality

### Project Information

<table>
<thead>
<tr>
<th>Project Principal Investigator(s)</th>
<th>Mirko Previsic (<a href="mailto:mirko@re-vision.net">mirko@re-vision.net</a>)</th>
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<tbody>
<tr>
<td>WPTO Lead</td>
<td>Erik Mauer</td>
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<td>William McShane</td>
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<td>Project Partners/Subs</td>
<td>University of Michigan</td>
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<td>Resolute Marine Energy</td>
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<td>Project Duration</td>
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Alignment with the Program

Marine and Hydrokinetics (MHK) Program Strategic Approaches

Data Sharing and Analysis

- Foundational and Crosscutting R&D
- Technology-Specific Design and Validation
- Reducing Barriers to Testing
Alignment with the MHK Program

Foundational and Crosscutting R&D

• Drive innovation in components, controls, manufacturing, materials and systems with early-stage R&D specific to MHK applications
• Develop, improve, and validate numerical and experimental tools and methodologies needed to improve understanding of important fluid-structure interactions
• Improve MHK resource assessments and characterizations needed to optimize devices and arrays, and understand extreme conditions
• Collaboratively develop and apply quantitative metrics to identify and advance technologies with high ultimate techno-economic potential for their market applications

• Development of controls framework that can be universally applied to a wide range of WEC archetypes and PTO configurations.
• Development and validation of controls frameworks using industry devices.
• Development and demonstration of a wave prediction system that is good-enough to implement MPC at sea - a worldwide first.
• Demonstration of MPC and wave-predicton on an at-sea prototype - a worldwide first.
• Development of various extensions to causal and non-causal controls frameworks allowing them to applied to different device types. Many of these methods were published.
Alignment with the MHK Program

Technology-Specific Design and Validation

- Validate performance and reliability of systems by conducting in-water tests of industry-designed prototypes at multiple relevant scales
- Improve methods for safe and cost efficient installation, grid integration, operations, monitoring, maintenance, and decommissioning of MHK technologies
- Support the development and adoption of international standards for device performance and insurance certification
- Evaluate current and potential future needs for MHK-specific IO&M infrastructure (vessels, port facilities, etc.) and possible approaches to bridge gaps

- Controls optimization for 3 different WEC device developers: CalWave, Ocean Energy, and Resolute Marine Energy.
- Detailed powertrain modeling for RME and development of loss model that can be used for controls purposes.
- Wave tank testing of RME’s Surge WEC and the OE Buoy to validate hydrodynamic response and control strategies.
- Validation of a wave-prediction system that is good-enough to enable MPC in WEC devices.
# Project Budget

## Total Project Budget – Award Information

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## Total Actual Costs

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Management and Technical Approach

Technical Approach:
• Focus on resolving technical issues encountered by our industry partners using iterative design-spiral approaches.
• Testing and validation: Wave tank testing of 3 devices, in-ocean testing of wave prediction system, in-ocean testing of controls system on a small WEC device.
• Core focus on developing “industry-ready” controls capabilities that can be applied to other WEC device developments.

Project Management:
• Lead at Re Vision Consulting. Core technical team in-house (7 team members).
• Accounting, contract compliance, and audited financials at Re Vision Consulting.
• Weekly Team Meetings with active external team partners to keep project on track.
• Quarterly meetings with DoE to review progress, address major issues and make strategic adjustments to our approach.
Technical Approach 2

Fundamental Controls Design Approaches:
- Linear MPC
- Non-Linear MPC
- Causal Control

Modifications for:
- Discrete force Ctrl in MPC
- Constraint handling in Causal Ctrl
- PTO loss model

Optimality Checks:
- Local minima issue in MPC
- Theoretical Limits
- RT Capability

Robustness:
- Failure Modes
- Convergence
- Wave prediction errors
Technical Approach 3

BEM Modeling (WAMIT/NEMO)

Systems Identification

PTO Option Modeling

Constraint Handling
- Force
- Motion
- Velocity
- Acceleration
- Powerflow
- Uni-Directional

PTO Loss Modelling

Non-Linearities
- Viscous Damping
- PTO Losses
- Hydro Forces
### Management and Technical Approach

#### Phase I Activities
- Detailed Implementation Planning
- RME - Controls Optimization
- RME - Wave Tank Testing
- OE - Controls Optimization
- OE - Wave Tank Testing
- CalWave - Controls Optimization
- Wave Prediction System Development
- Design of In-Ocean Demonstrator

#### Phase II Activities
- Detailed Design
- Build of Demonstrator
- RT Testing of Wave Prediction System
- Testing of Demonstrator

#### Milestones
- RME Device Optimized
- OE Buoy Optimized
- CalWave Controls Evaluated
- Wave-Prediction Buoys Built
- In-Ocean Validation of WP Accuracy
- Go/NoGo Review
- Demonstrator Ready for Deployment
- Complete Demo In-Ocean Testing

### Timeline

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<th>Activity</th>
<th>2016</th>
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End-User Engagement and Dissemination Strategy

End-user engagement:
- Engagement throughout the process with device developers.
- Device developers were on the project team to help develop and refine controls approaches and define the technical problems to be solved.

Dissemination
- Published a total of 10 journal articles, white papers and conference papers.
- Final technical report is forthcoming.

Commercialization Efforts:
- An off-the-shelf wave prediction system that can be used in any WEC application. Alternative markets are being evaluated.
- A tested offline controls optimization algorithm base that will be made available to industry through consulting engagements.
- RT control system that allows robust and fault tolerant algorithm execution on systems at sea.

Oceanenergy - OE Buoy TRL 6
Resolute Marine - SurgeWEC TRL6
Wave Carpet - TRL4
Technical Accomplishments

Wave Tank Validation at OSU
- Validation of Hydrodynamics
- MPC Testing
- Causal Control Testing
- 3 WEC Devices
Technical Accomplishments

In-Ocean Validation:
- Offshore Santa Cruz, CA
- 8kW Controls Demonstrator with 4 Quadrant PTO
- Built and tested 2nd 500W controls demonstrator
- > 20 Field campaigns completed
- Controls Validation Ongoing
Technical Accomplishments

Wave Prediction System:
- Developed RT Capable Wave Prediction Algorithm
- 4-8 Measurement buoys
- Benchmarked Measurement Accuracy at sea using RTK
- Validation of Wave Prediction Accuracy (RMS error of < 15%)
Future Work

While this project is sun-setting, there are various high-priority topics remaining to be addressed:
- R&D needs to be turned into commercial building blocks on the controls and wave-prediction aspects of this work.
- Fundamental improvements in non-linear MPC performance is required for many (more complex) device archetypes.
- Introducing constraints in causal controllers remains an issue that is difficult to address in a universal way.
- Controls system development needs to be turned into tools that can be made accessible to the broader industry. We would be willing to “open-source” our in-house tools developed if a suitable opportunity presented itself.

“If I have seen further it is by standing on the shoulders of Giants”
Isaac Newton, 1676