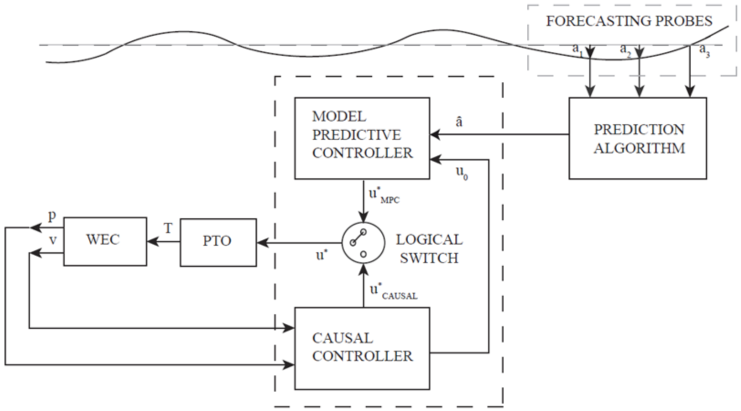

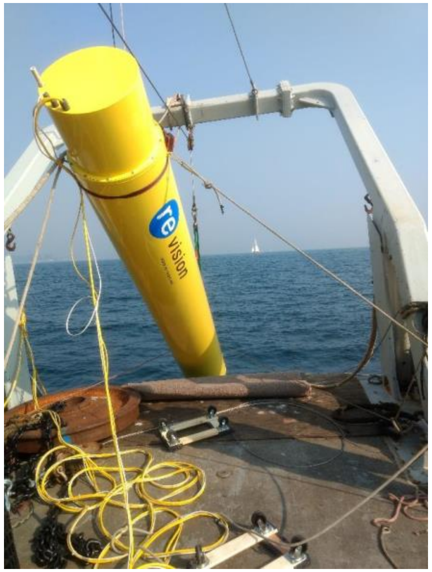

Optimal WEC Controls using Causal and MPC Methods

Project #: EE0007173

Marine and Hydrokinetics Program

10-9-2019

Mirko Previsic

Re Vision Consulting

Project Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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

Project Principal Investigator(s)

Mirko Previsic (mirko@re-vision.net)

WPTO Lead

Erik Mauer
William McShane

Project Partners/Subs

- University of Michigan
- Resolute Marine Energy
- CalWave
- Ocean Energy USA
- Integral Consulting
- HT Harvey & Associates
- Monterey Bay Research Vessels
- Evergreen Innovation
- Oregon State University
- UC Berkeley

Project Duration

- Project Start Date: 2/1/16
- Project End Date: 12/31/19

Alignment with the Program

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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

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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

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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

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Total Project Budget – Award Information		
DOE	Cost-share	Total
$2,499K	$624K	$3,124K

FY17	FY18	FY19 (Q1 & Q2 Only)	Total Actual Costs FY17–FY19 Q1 & Q2 (October 2016 – March 2019)
Costed	Costed	Costed	Total
$1,629k	$842k	$456K	$2,927K

Management and Technical Approach

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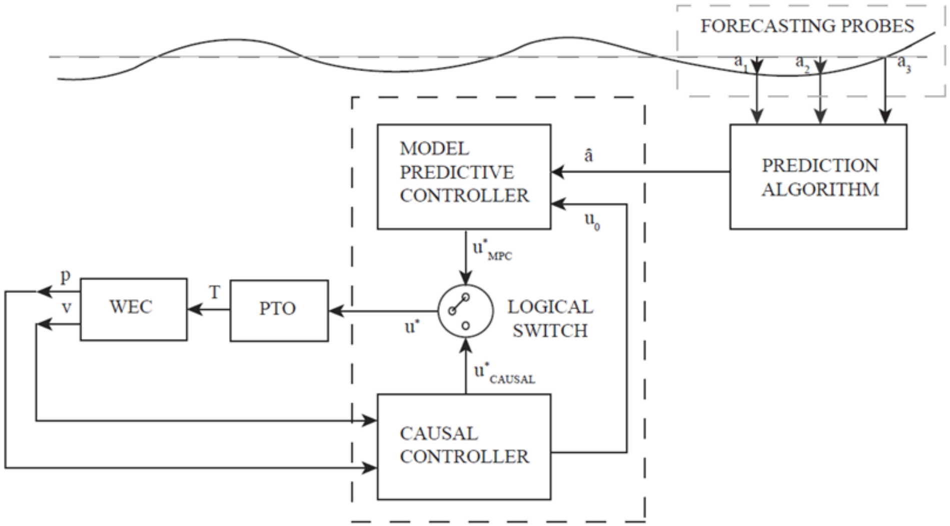
Technical Approach:

- 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:

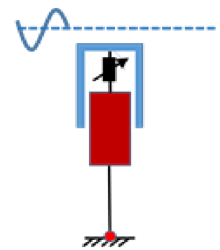
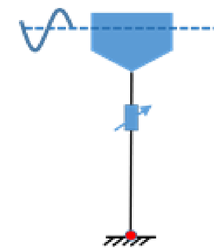
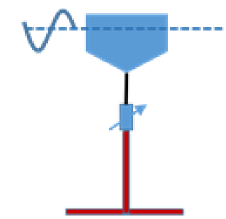
- Discreet force Ctrl in MPC
- Constraint handling in Causal Ctrl
- PTO loss model

Optimality Checks:

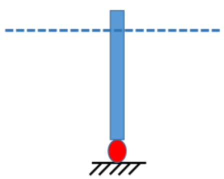
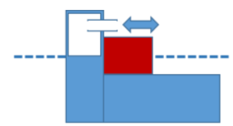
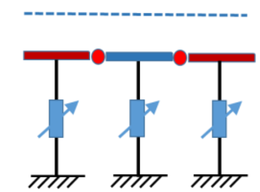
- Local minima issue in MPC
- Theoretical Limits
- RT Capability

Robustness:

- Failure Modes
- Convergence
- Wave prediction errors

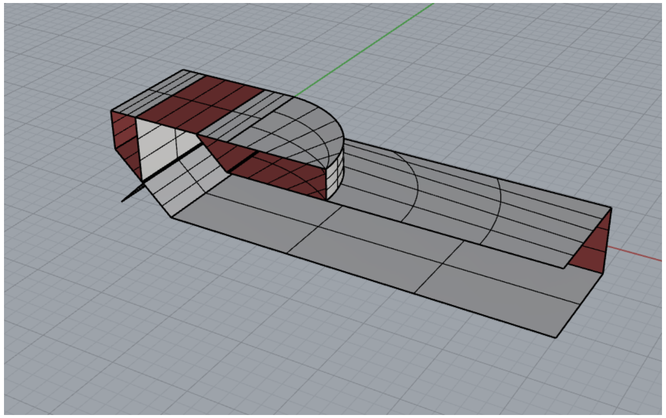
Topology	Subsea Pressure Differential	Heaving Point Absorber	Heaving Point Absorber
Reaction Point	Seabed	Seabed	Subsea Reaction Plate
Relevant DoF	1-DoF	1-DoF	3-DoF
# Bodies	1	1	>1
# PTO's	1	1	>1
Range of CD	<0.5	<0.5	0 – 4
Uni-Direct. Force Constraint	No	Yes	No
PTO End-Stop Constraint	Yes	No	Yes
Hydro Motion Constraint	Yes	Yes	Yes
Linear Wave Theory OK?	Yes	Yes	Yes
Non-Linear Froude Krylov	No	No	No

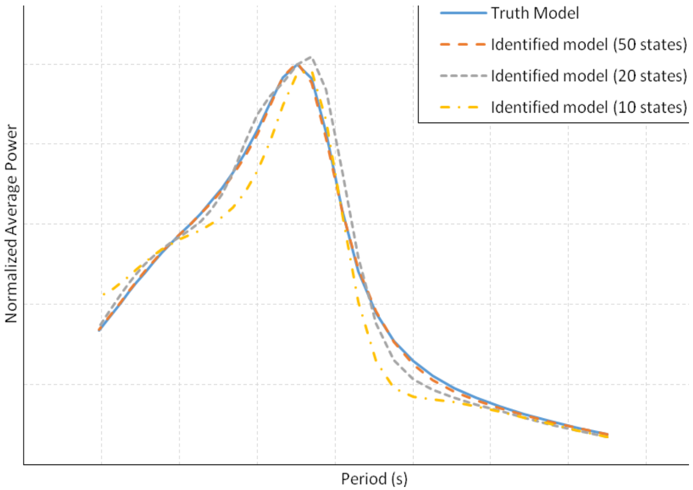
Topology	Shallow Water Surge	Backward Bent Duct	Subsea Pressure Differential
Reaction Point	Seabed	Self-Reacting	Seabed
Relevant DoF	1-DoF	4-DoF	1-DoF
# Bodies	1	1	>1
# PTO's	1	1	>1
Range of CD	1 - 5	<0.5	2 – 4
Uni-Direct. Force Constraint	No	No	No
PTO End-Stop Constraint	No	No	Yes
Hydro Motion Constraint	No	Yes (internal free surface)	No
Linear Wave Theory OK?	No	Yes	Yes
Non-Linear Froude Krylov	Yes	No	No

Technical Approach 3

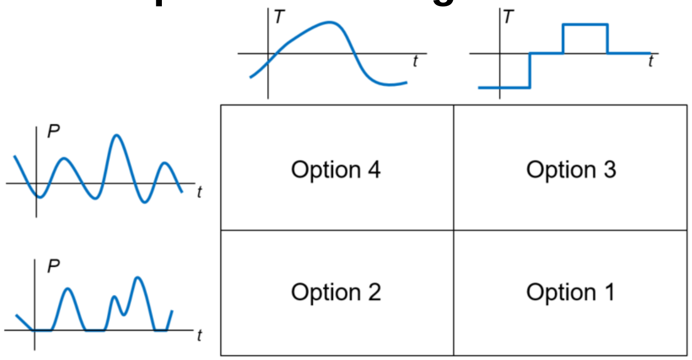
BEM Modeling (WAMIT/NEMO)



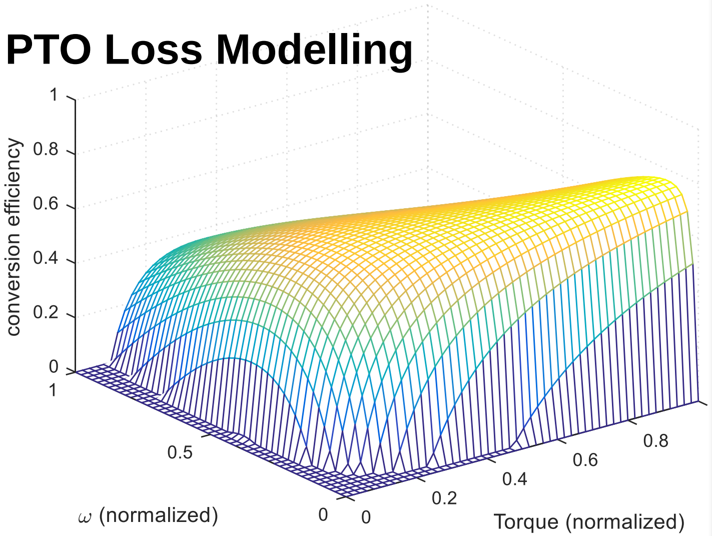
Systems Identification



PTO Option Modeling



PTO Loss Modelling



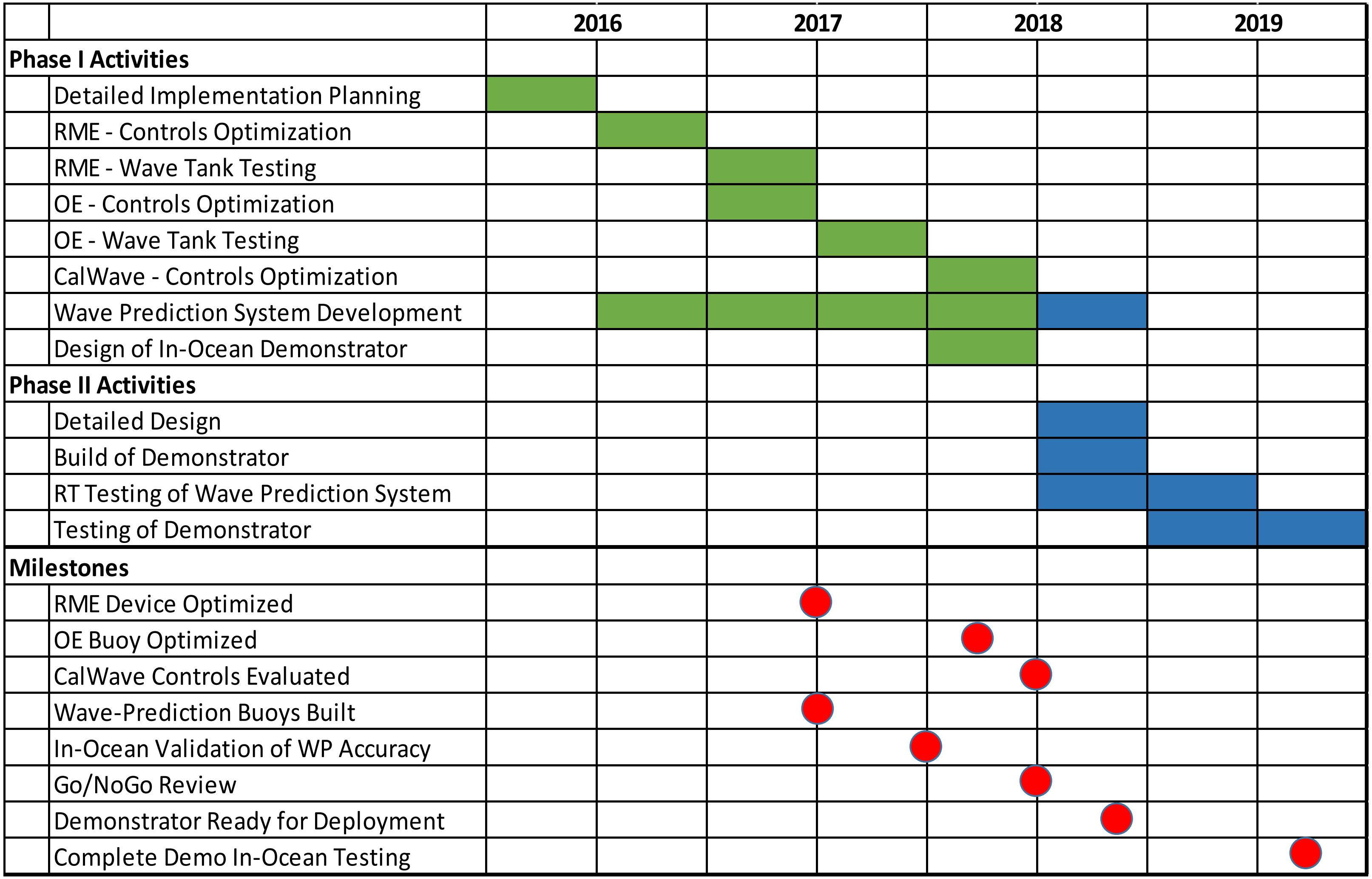
Constraint Handling

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

Non-Linearities

- Viscous Damping
- PTO Losses
- Hydro Forces

Management and Technical Approach



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

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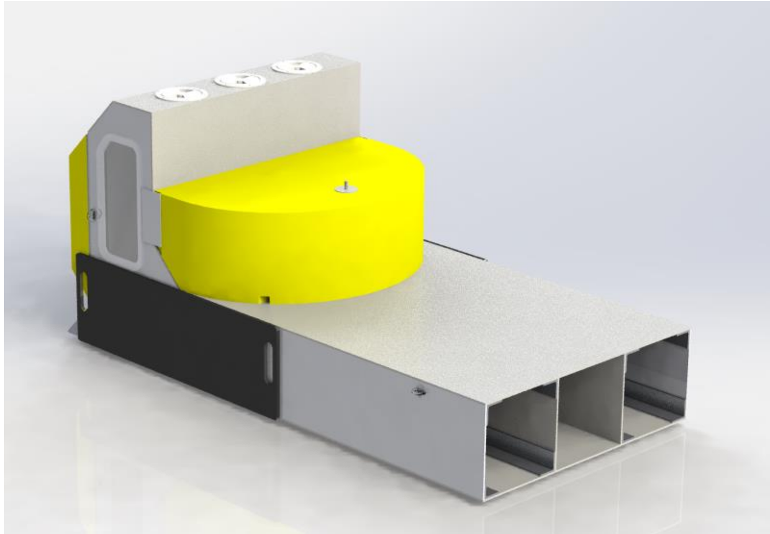
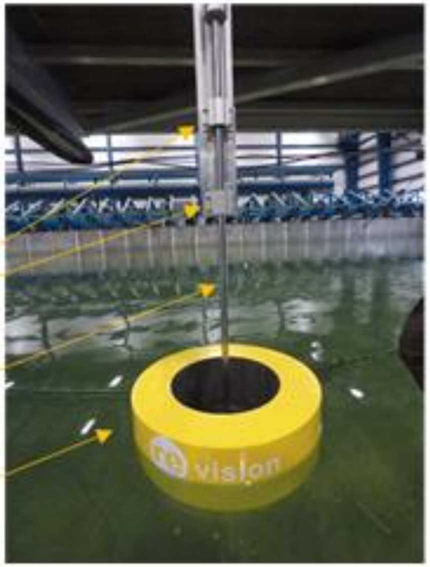
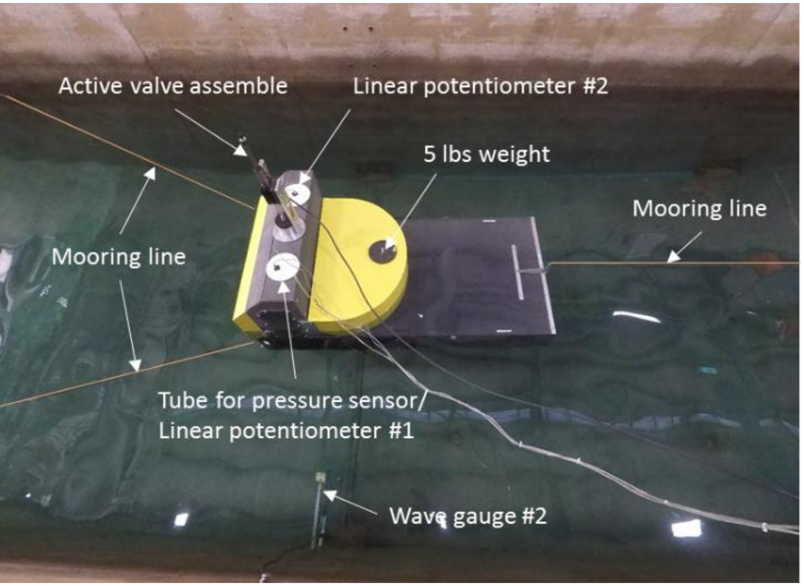
Wave Tank Validation at OSU

- Validation of Hydrodynamics
- MPC Testing
- Causal Control Testing
- 3 WEC Devices







Technical Accomplishments

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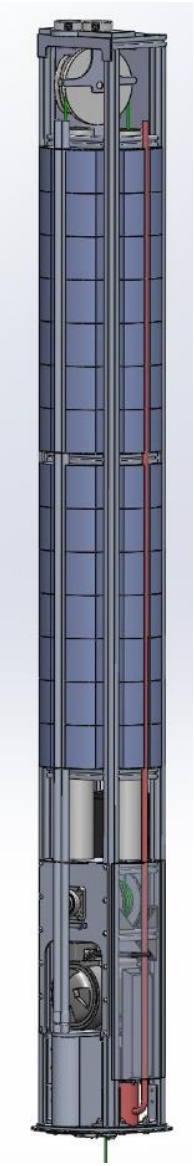
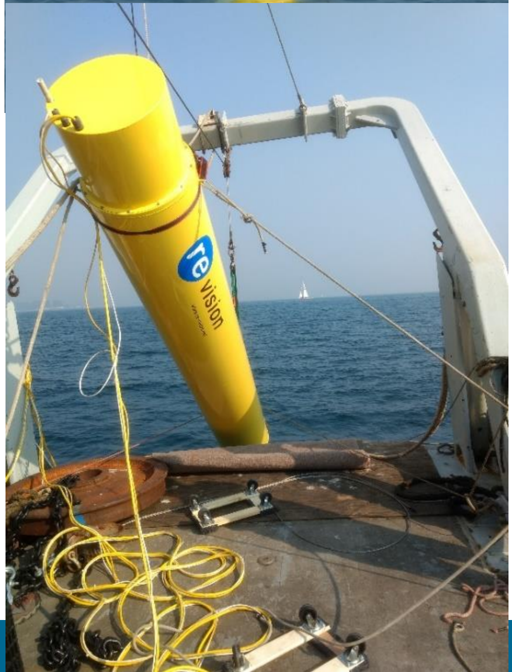
In-Ocean Validation:

- 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

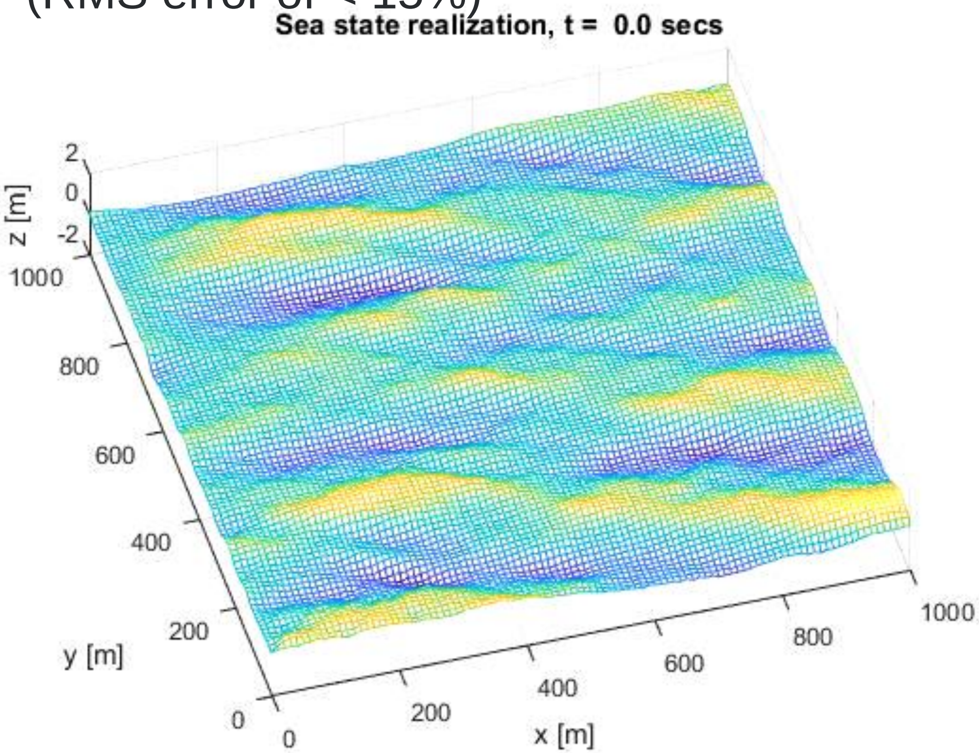


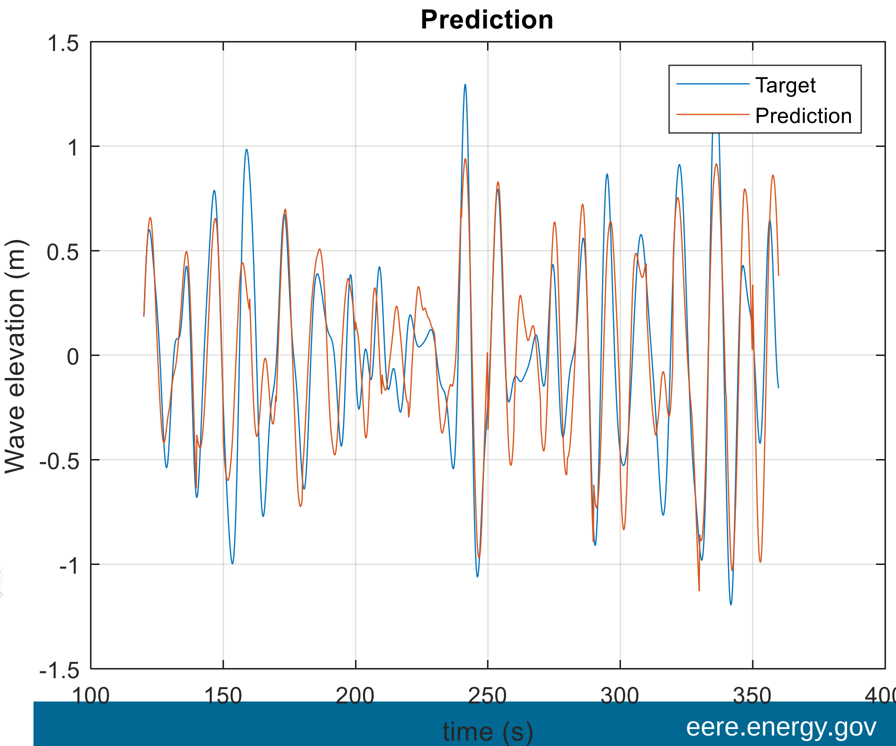


Technical Accomplishments

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

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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