Rebecca Fao, Chitra Sivaraman, and Budi Gunawan
National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (Sandia)

Rebecca.Fao@nrel.gov
Chitra.Sivaraman@pnnl.gov
Budi.Gunawan@sandia.gov

July 20, 2022

Photo: Scripps Institution of Oceanography/CalWave Power Technologies
Screen shots: Budi Gunawan, SNL
### Project Overview

#### Project Summary

In partnership with industry and academia, this multilab project is developing **software tools, instrumentation, and guidelines** that empower the marine energy (ME) community to **reliably** and **efficiently** collect, curate, process, manage, and share quality test data. These products fill gaps to enable high-quality field and laboratory validation, testing, demonstration, operation, and real-time data analysis that **provide critical information** used to feed all aspects of technology development and help **increase** the **technology readiness level** of ME converters.

#### Intended Outcomes

- **Increased** level of **data processing and analysis** at a **lower cost**
- Higher-quality **data products and reporting** that provide the **foundation** for **design**, **evaluation**, and **certification** of ME systems
- **Increased** data **accessibility, reuse, and sharing**
- Better ability to perform cross-project and **cross-data analysis** and **comparisons**
- **Increased measurement success** and higher-quality data produced in laboratory and field testing
- **Increased submission of high-quality data sets** to the Marine and Hydrokinetic (MHK) Data Repository in standardized formats
- **Higher quality** and breadth of **loads measurements** in field deployments
- **Increased understanding** of ME loads, resulting in **high reliability** of ocean deployed systems

### Project Information

#### Principal Investigator(s)

- Rebecca Fao, Chitra Sivaraman, and Budi Gunawan

#### Project Partners/Subs

- Oregon State University
- Florida Atlantic University
- CalWave
- AquaHarmonics

#### Project Status

- Ongoing

#### Project Duration

- Aug. 1, 2018–Present

#### Total Costed (Fiscal Year [FY] 2019–FY 2021)

- $2,415,000
To increase the value and success of the project testing/validation, the ME community needs:

- Access to experts
- Availability of proven hardware/software solutions
- Reduced cost of measurement and data processing
- Established practices that leverage existing knowledge, standards, and guidelines
- Shared experience and lessons learned.
<table>
<thead>
<tr>
<th>Gap 1: ME test data processing and analysis software</th>
<th>Gap 2: Micro Data Acquisition (DAQ) for small scale tank testing</th>
<th>Gap 3: Mechanical and PTO load sensors for larger scale field testing</th>
<th>Gap 4: Guidelines for instrumentation and measurement systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>• IEC compliant metric calculations</td>
<td>• Open-source design</td>
<td>• Mechanical and power take-off load guidance manual</td>
<td>• MRE testing</td>
</tr>
<tr>
<td>• Real-time data quality control and analysis</td>
<td>• Customizable</td>
<td>• Remote and wireless mooring load sensor</td>
<td>• MRE measurement</td>
</tr>
<tr>
<td>• Cloud processing</td>
<td>• Low cost</td>
<td>• Fiber optic hull strain monitoring</td>
<td>• Regulations, standards, guidelines, and certification</td>
</tr>
<tr>
<td>• Easy access to standardized code</td>
<td>• Low mass</td>
<td>• Structural health monitoring</td>
<td></td>
</tr>
</tbody>
</table>
Project Objectives: Relevance

Multi-Year Program Plan (MYPP) ME Program Activity 2 – Technology-Specific System Design and Validation

• Improves device response and signal quality for small-scale lab testing (MiniDAQ)
• Increases the understanding of ME loads resulting in high reliability of ocean-deployed systems (load sensor design and field validation)

MYPP ME Program Activity 3 – Reducing Barriers to Testing

• Produces software tools, instrumentation, and guidelines that enable successful testing by capturing and disseminating testing knowledge, ensuring high-quality data, enabling data analysis, reducing testing costs, and accelerating testing timelines

MYPP ME Program Activity 4 – Data Access, Analytics, and Workforce Development

• Enables quicker, cheaper, and consistent data processing, eliminating duplication of code development and reducing the risk of errors
• Aids device certification through turnkey IEC-standards-compliant data processing
• Enable near-real-time data processing and analysis to assist operator in making critical decisions
• Enables submission of high-quality data sets to the MHK Data Repository in standardized formats, leading to improved data preservation and knowledge capture
Project Objectives: Approach

1) Develop, disseminate, and maintain open-source software tools and repositories for data ingestion, reduction, conditioning, quality control, transformation, calculation, and visualization, bringing validated ME data processing code together for ease of discovery and utilization.

2) Design and construct a small and low-cost DAQ system, providing a standard small DAQ solution that developers and researchers can easily leverage.

3) Develop and demonstrate reliable mechanical load measurement instrumentation that meets the needs of ME field testing, standardizing loads measurements.

4) Develop and disseminate experience-based guidelines for laboratory and field measurement and testing, reducing the loss of knowledge over time and allowing the industry to build on previous work.

MiniDAQ, Credit: Oregon State University
Mooring load measurements
Finite element analysis of wave energy converter and power take-off belt mooring
MHKiT tidal resource assessment module
Screen Shots: Budi Gunawan, SNL
### Project Objectives: Expected Outputs and Intended Outcomes

#### Outputs:
- **Software/tool/model**: MHKiT-Python and MATLAB, structural model of wave energy converter power take-off mooring lines, ME Code Hub, PRIMRE Code Catalog, ME Data Pipeline
- **Hardware**: Open-source low cost, small, and lightweight DAQ system for small-scale testing and underwater wireless telemetry system for load measurements
- **Publications**: Scientific papers (10+), best-practices guidance, conference presentations
- **Training**: Manuals, documentation, tutorial videos, webinars
- **Data sets**: Mooring load data from ocean wave energy converter deployment
- **Standards**: Improvement to IEC -3 Mechanical Load Measurements Technical Standard

#### Outcomes:
- Increased level of data processing and analysis at a lower cost with easy access to standardized data processing and analysis tools
- Better ability to perform cross-project and cross-data analysis and comparisons
- Ability to standardize and process data in real time on the cloud, allowing for real-time operational decision making
- Increased measurement success and higher-quality data produced in laboratory and field testing, leading to improved knowledge capture and pathways to commercialization
- Increased understanding of ME loads, resulting in high reliability of ocean-deployed systems
- Further development, increased use, and broader acceptance of IEC standards
Project Timeline

**FY 2019**
- Completed IEC functions for wave, river, and tidal
- Populated Code Catalog and Code Hub integration with PRIMRE
- MiniDAQ design requirements
- Load sensor system design

**FY 2020**
- Released MHKiT v0.1.0
- Completed Code Catalog and Code Hub integration with PRIMRE
- Guidelines document for mechanical and power take-off load sensors for larger-scale field testing
- Completed load sensor system dry testing with CalWave
- Completed MiniDAQ bench testing

**FY 2021**
- Released MHKiT v0.4.0
- First release of ME Data Standards & Ingestion Pipeline
- Released MiniDAQ V 1
- Sea deployment of CalWave wave energy converter and wireless mooring load system
## Project Budget

<table>
<thead>
<tr>
<th></th>
<th>FY 2019</th>
<th>FY 2020</th>
<th>FY 2021</th>
<th>Total Actual Costs FY 2019–FY 2021</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NREL</td>
<td>$218,000</td>
<td>NREL $219,000</td>
<td>NREL $195,000</td>
<td>NREL $632,000</td>
</tr>
<tr>
<td>PNNL</td>
<td>$102,000</td>
<td>PNNL $151,000</td>
<td>PNNL $189,000</td>
<td>PNNL $442,000</td>
</tr>
<tr>
<td>Sandia</td>
<td>$390,000</td>
<td>Sandia $523,000</td>
<td>Sandia $428,000</td>
<td>Sandia $1,341,000</td>
</tr>
<tr>
<td>Total</td>
<td>$710,000</td>
<td>Total $893,000</td>
<td>Total $812,000</td>
<td>Total $2,415,000</td>
</tr>
</tbody>
</table>
End-User Engagement and Dissemination

Online Repositories: Open source tools and designs are hosted at online repository, e.g., MHKiT, ME Data Pipeline, and MiniDAQ on GitHub. End users: ME developers and researchers.

Knowledge Hubs: Open-source wikis and databases provide guidance for MRE testing, measurement, and data processing based on experience, lessons learned, standards, and best practices.

Webinars and Workshops: Conducted for industry, academia, and focus groups throughout the ME space, webinars have been recorded and posted to YouTube for future reference.

Scientific Articles: Journal and conference articles and presentations targeting industry and academia have been published.

Cross-Project Integration: We have leveraged contributions from other WPTO- and non-WPTO-funded projects in other domains to strengthen the core framework.

Industry and University Partnerships: We leveraged developers' ocean testing projects (e.g., CalWave's and AquaHarmonics' WPTO FOA 1663 projects) and knowledge at university partners (Oregon State, Florida Atlantic).

Feedback: We seek feedback to improve tools through industry surveys.

News Articles: We email news through Tethys Engineering, WPTO News, and Lab News.
Performance: Accomplishments and Progress

Enabled standardized data processing through verified, open-source tools – leading to rapid, consistent data analysis and knowledge capture when we:

- Released MHKiT Python and MATLAB (MHKiT- Python had over 11,000 all time downloads [in 3 years]) and twice-yearly updates, bringing major function improvements to users.
- Released the initial version of the ME data pipeline (16,000 all-time downloads [in 1 year]) with 33 public repositories using tsdat.

Simplified discovery of ME relevant code and guidelines - saving time and money needed to create new code and research best practices when we:

- Released the MRE Code Catalog, PRIMRE Code Hub, and Telesto.
- Published a guidelines document for mechanical and power take-off load sensors for larger-scale field testing.
- Released a data quality control standards document.

Improved data collection capabilities for small scale testing, increasing knowledge capture, when we:

- Released MiniDAQ design and performance validation.

Developed and demonstrated new loads measurement capabilities, easing the ability to collect critical loads data, when we:

- Completed ocean testing for mooring load system with Calwave.
Future Work

Expand software tools to include additional capabilities as the ME industry evolves and grows:

• Release a new MHKiT to include met-ocean, Powering the Blue Economy, mooring, noise, and other processing capabilities based on user feedback.
• Develop new capabilities for ME Data Pipeline: Transformation pipelines, built-in quality checks and controls, and built-in support for a common data format.

Continue user engagement and training:

• Develop training and guidance materials for user-developed MHKiT functionality.
• Develop ME Data Pipeline end-user support and dissemination.

Complete the first phase of knowledge dissemination:

• Continue to populate Telesto with additional guidance (under the PRIMRE project).

Demonstrate and validate field and laboratory hardware:

• Load measurement sensor design and field testing in conjunction with AquaHarmonics' ocean deployment in FY 2023/2024.
• Demonstration of MiniDAQ on a wave energy converter laboratory testing (wave basin).
Project Links and Publications – Reference

MHKit and MiniDAQ Dissemination

- https://mhkit-software.github.io/MHKiT/
- https://github.com/ME-Data-Pipeline-Software
- https://github.com/tsdat
- https://github.com/bretbosma/Mini-DAQ
- https://doi.org/10.5281/zenodo.5042211

Scientific Articles

- Sterling Olson, Rebecca Fao, Kelley Ruehl, Frederick Driscoll, Budi Gunawan, Chitra Sivaraman, Carina, Lansing, and Hristo Ivanov. 2021. "The Marine and Hydrokinetic ToolKit (MHKit) for Data Quality Control and Analysis." Presented at European Wave and Tidal Energy Conference 2021, Plymouth, United Kingdom, Sept. 5–9, 2021.