Wind Energy with Integrated Servo-Control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems

Daniel Zalkind,[1] Jason Jonkman,[1] Matthew Hall,[1] Garrett Barter,[1] James Allison,[2] Daniel Herber,[3] and Alan Wright[1]

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Wind Energy with Integrated Servo-control (WEIS): A Toolset To Enable Controls Co-Design of Floating Offshore Wind Energy Systems

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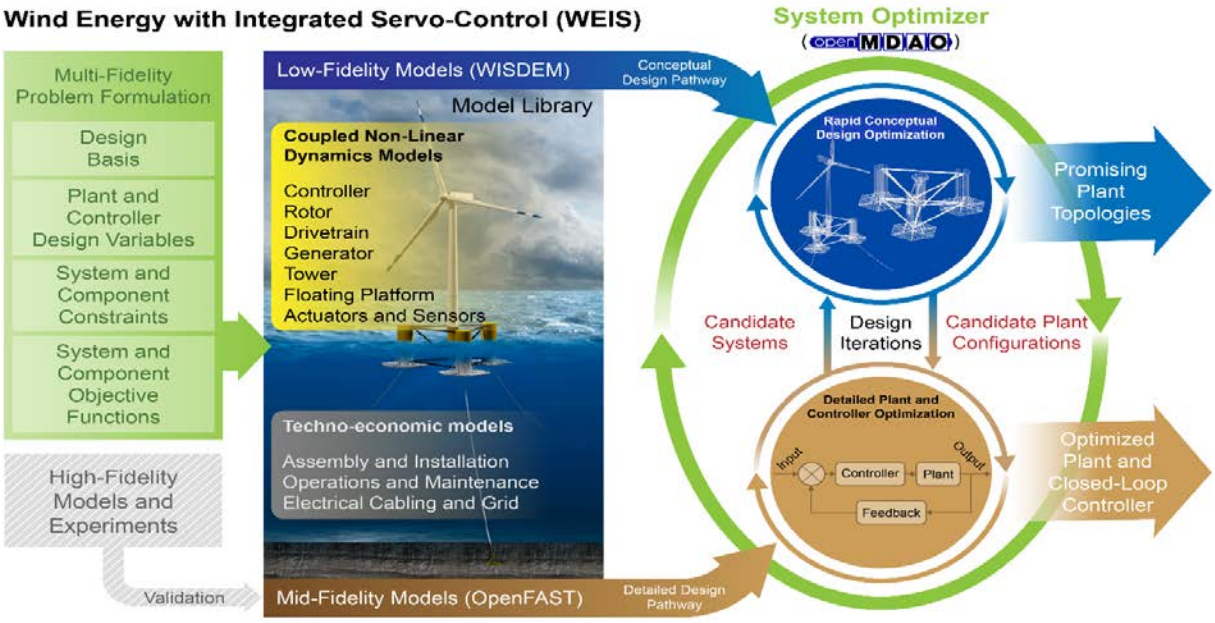

Award:	18/CJ000/07/13 DE-AR0001182
Lead Recipient:	NREL
Project Title:	Wind Energy with Integrated Servo-control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems
Program Director:	Dr. Mario Garcia-Sanz
Principal Investigator:	Dr. Daniel Zalkind, Dr. Alan Wright (previously)
Contract Administrator:	Dr. Mario Garcia-Sanz
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Public Executive Summary

The Wind Energy with Integrated Servo-control (WEIS) toolset provides the offshore wind industry and research communities with an open-source, user-friendly, and flexible toolset to enable control co-design (CCD) of land-based, fixed-bottom, and floating offshore wind turbines (FOWTs). The tool generates system-optimal solutions to solve the design problems of the FOWT industry, leading to new performance levels and ultimately reducing the cost of energy.

WEIS is built on the foundation of previously existing modeling tools. The systems engineering tool WISDEM® was extended to include control methods and aeroelastic simulation tools at multiple fidelity levels. To translate models from systems engineering models to simulation models, a variety of pre- and post-processing methods were integrated and updated in the WEIS toolset, along with the ability to run standard design load cases. This integrated design environment allows users to model FOWTs, along with controls, across multiple fidelity levels, evaluating the cost and performance at each stage of design.

Several modeling advancements were realized during the WEIS projects. The aeroelastic simulator OpenFAST—including the nonlinear time-domain formulation and linearization functionality—was extended to support the modeling needs of ATLANTIS Area 1 teams and for application to future innovative FOWT designs. Additionally, a new frequency-domain tool, RAFT, was developed to provide efficient, frequency-domain modeling of FOWTs with limited and fully automated preprocessing steps, enabling rapid design evaluation within the optimization loop.

New CCD methods for FOWTs were developed during this project. The software framework for running optimizations with simulations in the loop was integral to the project's success. Theoretical CCD methods were made realizable with advances in the surrogate modeling of FOWTs. These methods were demonstrated in benchmark case studies. The team used surrogate models in a nested CCD solution, where an outer-loop problem uses WEIS's glue code to change platform design variables while the inner loop solves for the optimal control solution of each design. The team also demonstrated a multi-fidelity optimization of the IEA 15-MW reference turbine. RAFT was used to optimize a reference semisubmersible's dimensions. Linearized OpenFAST was used to optimize the controller, which could be reproduced with nonlinear closed-loop control. Finally, a nonlinear optimization of the tower with nonlinear control parameters demonstrated the highest level of design optimization and fidelity.

Our planned improvements in the next phase of the WEIS project will aim to increase the user base and integrate WEIS into industry design processes. Modeling improvements are aimed at supporting the latest innovative platform designs and using WEIS to perform certification-level studies. Users will be able to include their own models and measures for performance. The WEIS team is planning interviews and a set of case studies with industry advisors to demonstrate that WEIS can be used to solve realistic industry CCD design problems for FOWTs.

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Acknowledgements

The WEIS project would not be possible without the financial support from ARPA-E and the guidance provided by the program director, Dr. Mario Garcia-Sanz. Dr. Carlos Noyes also provided helpful guidance throughout the project. Subcontractors at the University of Illinois Urbana-Champaign and Colorado State University, respectively led by Prof. James Allison and Prof. Dan Herber, made major contributions to the WEIS project. We are also grateful for the support of our External Advisory Board, who provided feedback and inspiration for future work.

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Table 1. Key Milestones and Deliverables. 1

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Accomplishments and Objectives

This ARPA-E ATLANTIS Program award allowed the National Renewable Energy Laboratory (NREL), along with its collaborators at the University of Illinois Urbana-Champaign (UIUC) and Colorado State University (CSU), to demonstrate control co-design (CCD) solutions in an open-source software that can be used for future collaborations with industry partners. The project focused on building a software framework and methods for modeling floating wind turbines across fidelity levels, with control solutions, cost estimates, and drivers to optimize and analyze design trade-offs and reduce the levelized cost of energy.

Tasks and milestones were elaborated in Attachment 3, Technical Milestones and Deliverables, at the beginning of the project. Actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Software and Program Management 1.1 Software development plan 1.2 Data flow diagrams 1.3 Establish WEIS functional requirements 1.4 Collaboration workshop at ARPA-E Summit or ATLANTIS Annual Review 1.5 End-of-project report	**Actual Performance:** 1.1 (Completed Q1) Delivered software development plan for WEIS, including (1) software language breakdown, (2) GitHub repository practices, (3) usage of third-party software and libraries, (4) documentation and code style standards. 1.2 (Completed Q2) Issued data flow conceptual diagrams to illustrate how user inputs and analysis sequences progress through the WEIS modules. 1.3 (Completed Q1) Documented the functional requirements of WEIS based on interaction with the External Advisory Board and their priorities. 1.4 (Completed Q6) Conducted a workshop highlighting the interim release of WEIS and demonstrating its use to perform a CCD optimization for a floating system (spar example). A workshop was held on May 19, 2021 with approximately 40 participants composed of External Advisory Board members and other interested parties. 1.5 (Completed Q10) Submitted final report containing a review of the work completed in the OpenFAST, RAFT, and Integration subtasks as well as a summary of the benchmark case studies and our plans for future work.

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Tasks	Milestones and Deliverables
Task 2: Control Co-Design 2.1 Complete prototype method for CCD approach for open loop optimal control 2.2 (Revised) Complete prototype CCD method for closed-loop control and multi-fidelity strategy in support of all benchmark case studies	**Actual Performance:** 2.1 (Completed Q4) Completed prototypes of nested CCD approaches for implementation into WEIS using reduced-order floating wind turbine models. 2.2 (Completed Q8) Developed a method for reproducing the open-loop optimal control with a closed-loop controller and integrated it into WEIS; method was used in Benchmark Case Study 3. Original milestones removed in SOPO revision: - Completed first prototype method for designing closed-loop controllers based on open-loop optimal control results in WEIS. - Completed first prototype of a CCD coordination strategy between model fidelity levels
Task 3: Frequency-Domain Modeling 3.1 Frequency-domain hydrodynamics in WISDEM 3.2 Interim release of WISDEM improvements 3.3 (Revised) Completion of Level 1 frequency-domain model (WEIS-RAFT) in support of Benchmark Case Study 2	**Actual Performance:** 3.1 (Completed Q4) Implemented all components of the frequency-domain floating support structure model. Work is ongoing to verify accuracy and compatibility with different design configurations. 3.2 (Completed Q4) Implemented the capabilities described in M3.1 in a new software package called RAFT. An interim release of the model was published along with input files for three support structure designs. 3.3 (Completed Q7) The WEIS-RAFT team completed a verification of the Level 1 RAFT model against OpenFAST for three reference floating wind turbine designs and achieved good levels of agreement for the fidelity level. RAFT v1 was released on GitHub, along with online documentation and several example files. RAFT was used in Benchmark Case Study 3, including platform and rotor performance, and in frequency-domain representations of design load cases (DLCs). Original milestones removed in SOPO revision: - Frequency-domain rotor performance in WISDEM® completed - Frequency-domain DLC driver in WISDEM - Frequency-domain control module in WISDEM - Major release of WISDEM

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Tasks	Milestones and Deliverables
Task 4: OpenFAST Modeling 4.1 Vortex free-wake aerodynamics in OpenFAST 4.2 Interim release of OpenFAST improvements 4.3 Linearization with respect to design parameters in OpenFAST 4.4 Active and passive controllers in OpenFAST 4.5 (Revised) Major release of OpenFAST in support of benchmark case studies 1a, 1b, and 2	Actual Performance: 4.1 (Completed Q4) Enhanced the OLAF model of AeroDyn with improved physics, solution options, robustness, and user friendliness. 4.2 (Completed Q4) Completed the interim release, which included updates to OLAF, substructure flexibility and member-level loads, and new active and passive platform-based control actuators in support of Area 1 teams. 4.3 (Completed Q6) After working to develop a theoretical basis, the team decided it would be better to implement linearization of OpenFAST with respect to design parameters by scripts that call OpenFAST within WEIS. The scripting, verification, and an illustrative case study were completed. Moreover, source code profiling was used to identify computational bottlenecks where future code improvements could best target the expense of linearizing. 4.4 (Completed Q7) Completed the time-domain implementation of active and passive platform-based controllers. Completed an interface to the active controllers through Simulink and ROSCO and on linearization of the new control methods. Completed linearization implementation and verified the approach. 4.5 (Completed Q8) Updated the wave kinematics and wave-excitation loads based on the displaced position/orientation of the floater; this change improved the accuracy of hydrodynamic load calculations for large floater motion. Both the improved nonlinear hydrodynamics and new active/passive control functionality from M4.4 were released to the latest version of OpenFAST. Original milestones removed in SOPO revision: - Nonlinear hydrodynamics in OpenFAST for large yaw motion - Rectangular members in OpenFAST - Full implementation in OpenFAST of linearization with respect to design parameters

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Tasks	Milestones and Deliverables
Task 5: WEIS Integration 5.1 Common geometry parameterization 5.2 WEIS Python driver for OpenFAST modules 5.3 OpenMDAO extensions for additional libraries 5.4 Interim release of WEIS 5.5 (Revised) Integration of WEIS components and functionality to support all benchmark case studies	Actual Performance: 5.1 (Completed Q3) The WEIS team completed the common geometry parameterization formulation. Details were provided in the Q3 report. 5.2 (Completed Q4) A dynamic OpenFAST library was developed that can be executed from Python without writing large output files. Automation of OpenFAST preprocessing was also completed. 5.3 (Completed Q3) Assessed and added optimization packages from NLOpt and DAKOTA packages. 5.4 (Completed Q4) Released WEIS v0.1, which can be used for Level 3 (nonlinear time domain) optimization of a floating substructure, including simple co-design. 5.5 (Completed Q7) The WEIS Integration team successfully integrated the direct transcription quadratic programming (DTQP) solver into WEIS, along with the latest versions of many of the core packages: RAFT, OpenFAST, ROSCO, WISDEM. Original milestones removed in SOPO revision: - Global DLC driver: The DLC driver exists in WEIS and was used to simulate and determine the design-driving load cases in the benchmark case studies. - Common variable and linearization sharing: Linearizations generated in WEIS were used in Benchmark Case Study 2. - Multifidelity optimization strategy implementation: A prototype multi-fidelity optimization strategy is presented in a journal article, and another method was demonstrated in Benchmark Case Study 3. - CCD optimization strategy implementation: An overall strategy was not implemented, but three different methods are presented in the benchmark case studies. - Graphical user interface: not implemented. - Sample problems and additional documentation: Benchmark Case Study 3 is available as a WEIS example along with others. Documentation is in progress and is part of Phase 2 plans. - Release of version 1.0 of WEIS: Released on April 28, 2022, with Benchmark Case Study 2 functionality.

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Tasks	Milestones and Deliverables
Task 6: Cross-Collaboration Tasks (CCTs) 6.1 Incorporation of VAWT physics and OWENS (CCT-2) 6.2 Use WEIS to optimize UMaine Floater (CCT-6) 6.3 Incorporation of UCF control solutions (CCT-8) 6.4 Model validation with experimental data (CCT-9)	**Actual Performance:** 6.1 (Completed Q12) The ARCUS team coupled OWENS-OpenFAST to model floating vertical axis wind turbines and verified the code against stand-alone OpenFAST. A journal article was published in *Energies* on the code development and verification results. 6.2 (Completed Q11) Researchers from the University of Maine (UMaine) visited NREL during the week of July 18, 2022; NREL hosted a workshop demonstrating the features of WEIS. UMaine ran publicly available WEIS examples and adapted them to suit the NASAFloat platform. In the final deliverable, the optimization of the NASAFloat TMD parameters determined using WEIS were compared to those determined by the UMaine team. 6.3 (Completed Q10) The UCF and NREL teams developed a method for porting controllers from Dymola to OpenFAST via MATLAB-Simulink. To demonstrate this capability, elements of ROSCO (such as the above-rated blade pitch speed controller) were developed in Modelica and ported to Simulink via a functional mock-up unit. The Dymola-developed controller was implemented in a Simulink model that uses OpenFAST as the nonlinear floating wind turbine simulator. A journal paper demonstrating these methods is was published in *Wind Energy*. 6.4 (Completed Q12) The WEIS team supported the development of the specification document for FOCAL test campaigns, developed and calibrated the OpenFAST model, and submitted the simulation results for all load cases. The results were presented at the DeepWind conference in January 2023. A journal article was drafted and submitted to internal NREL reviewers.
Task 7: Tech-to-Market 7.1 Tech-to-Market milestone 1 7.2 Tech-to-Market milestone 2 7.3 Tech-to-Market milestone 3 7.4 Tech-to-Market milestone 4 7.5 Tech-to-Market milestone 5	**Actual Performance:** 7.1 (Completed Q1) Completed draft Tech-to-Market plan and submitted on April 30, 2020. Comments received from ARPA-E on May 7. Virtual meeting was held with ARPA-E to discuss plan comments (July 16, 2020). 7.2 (Completed Q2) Finalized the next Tech-to-Market plan draft by revising the Q1 draft, addressing comments by ARPA-E and comments during the July 16 meeting with ARPA-E. 7.3 (Completed Q7) Completed the Tech-to-Market plan revision based on lessons learned over the previous quarters. 7.4 (Completed Q10) Submitted latest Tech-to-Market plan draft to ARPA-E. Incorporated comments from External Advisory Board meeting into final plan draft. A final version of the draft was sent to ARPA-E in April 2022.

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Tasks	Milestones and Deliverables
Task 8: Benchmark Case Studies M8.1 Benchmark Case Study 1a Completion M8.2 Benchmark Case Study 1b Completion M8.3 Benchmark Case Study 2 Completion M8.4 Benchmark Case Study 3 Completion	**Actual Performance:** 8.1 (Completed Q9) Completed Benchmark Case Study 1 using a nested CCD approach with DTQP for optimal control inputs and outer-loop design variables and constraints. 8.2 (Completed Q9) Completed Benchmark Case Study 2; the team used a simplified low-order model and a nested CCD formulation. The team investigated how derivative function surrogate modeling can be refined to provide a more robust surrogate model for the inner- and outer-loop optimizers. Appropriate constraints (tower stress, etc.) were developed and implemented. 8.3 (Completed Q9) The NREL team completed Case Study 3: (1) using RAFT to optimize a platform design, (2) using DTQP to generate open-loop control solutions, which can be reproduced using a closed-loop controller, and (3) optimizing tower, control, and tuned mass damper parameters in Level 3 OpenFAST models. The NREL team combined these fidelity levels using the outputs of lower-fidelity levels as inputs to the higher-fidelity level optimizations.

Several models were used in the development of WEIS. The highest-fidelity model, OpenFAST, has been validated in several Offshore Code Comparison campaigns. Lower-fidelity models, in RAFT and WISDEM, were typically validated with respect to OpenFAST models. All models are openly available on GitHub.

Project Activities

The WEIS team developed a software tool for modeling, simulating, and optimizing FOWTs, with a goal of demonstrating that designs with lower cost could be realized by using this integrated CCD environment. Several case studies demonstrate the tool's use on FOWT design problems.

Project Outputs

A. Journal Articles

Jonkman, J.M., E.S.P. Branlard, and J.P. Jasa. 2022. "Influence of Wind Turbine Design Parameters on Linearized Physics-Based Models in OpenFAST." *Wind Energy Science* 7(2): 559–571. https://doi.org/10.5194/wes-7-559-2022.

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Wang, L. et al. 2023. “Experimental Validation of Models of a Hull-Based Tuned Mass Damper System for a Semisubmersible Floating Offshore wind Platform.” Journal of Physics: Conference Series 2626: 012067. DOI: 10.1088/1742-6596/2626/1/012067.

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Bayat, S., Y.H. Lee, and J.T. Allison. 2025. “Nested Control Co-Design of a Spar Buoy Horizontal-Axis Floating Offshore Wind Turbine.” *Ocean Engineering* 328: 121037. https://doi.org/10.1016/j.oceaneng.2025.121037.

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B. Papers

Jonkman, J., A. Wright, G. Barter, M. Hall, J. Allison, and D.R. Herber. 2020. “Functional Requirements for the WEIS Toolset to Enable Controls Co-design of Floating Offshore Wind Turbines.” ASME 2020 3rd International Offshore Wind Technical Conference, Boston, MA, Feb. 16–17, 2021.

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Status Reports

N/A

C. Media Reports

N/A

D. Invention Disclosures

N/A

E. Patent Applications

N/A

F. Licensed Technologies

N/A

G. Networks/Collaborations Fostered

Several External Advisory Board members have reached out for specific support in using WEIS.

H. Websites Featuring Project Work Results

Several open-source tools have released software as a result of the WEIS project:

- https://github.com/WISDEM/WEIS
- https://github.com/WISDEM/WISDEM
- https://github.com/WISDEM/RAFT
- https://github.com/OpenFAST/openfast
- https://github.com/NREL/ROSCO

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I. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

N/A

J. Awards, Prizes, and Recognition

N/A

Follow-On Funding

Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award.

Table 2. Follow-On Funding Received.

Source	Funds Committed or Received
ARPA-E	$3M

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