Project Title

Open Wave-Energy Control System Development Platform

Federal Agency and Award Number

DOE – EERE

DE-EE0009444

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Project Period of Performance

10/1/2021 - 3/31/2026

Reporting Period End Date

12/31/2024

Accomplishments

a) Major Goals and Objectives

The primary goal of this project is to create a software infrastructure for the MBARI Wave Energy Conversion buoy that will allow outside collaborators to develop control algorithms that take advantage of all features of the MBARI buoy, and execute these algorithms during the regularly scheduled deployments. The intent of this is to provide an at-sea test-bed for controls researchers that they would not ordinarily have access to, and promote real-world control system research and testing in this manner. The project contains three main activities;

i) Buoy Software Infrastructure: This is the development of an application programming interface (API) on the buoy system that provides developers consistent access to all sensor data on the buoy and a means by which to programmatically specify control inputs to the wave-energy converter. With this API, developers will be able to concentrate almost entirely on the control algorithm portion of the task, without needing to develop specific expertise in the lower level software and hardware infrastructure of the wave-energy converter. The architecture of the MBARI wave-energy converter buoy is well suited to this abstraction and allows new control code to be uploaded and executed in this model, while the buoy is at sea. It is intended to be routine to perform design iterations in which code is uploaded and run, results analyzed, modifications made and new code uploaded and run, without the need to recover the system.

ii) Simulation Environment: In order for developments using the API to proceed efficiently, a simulator is also required that allows newly developed code to be tested before deployment on the hardware. A key requirement of this simulator is that it provides an API that is identical to the buoy API. Meeting this requirement means that code that runs in the simulation environment can also run entirely unchanged on the buoy while it is at sea. This simulation environment also will provide some safety checks on code before it is run on the buoy, and allow researchers to do some algorithm performance testing before at-sea testing. The simulator is being developed to run faster than real-time, and will have a range of settings that balance code execution speed and simulation fidelity.

iii) Marketing and Outreach: The most challenging component of this project is developing engagement with our target users. There are a wide range of potential users and we are targeting academic and non-profit institute researchers as per the funding opportunity announcement. We also envision teaching opportunities for this platform and can imagine a university course in marine hydrokinetic energy harvesting being developed that uses the materials resulting from this project. We are planning a number of activities such as webinars, seminars, and conference events to support this. Additionally, we have included requirements in our software development and documentation specification for ease of use for individuals new to ROS and this type of programming.

To facilitate these activities, this project included Open Robotics Software Foundation (ORSF) as a significant subaward. ORSF develops and promotes the popular “Robot Operating System” (ROS, https://www.ros.org) which is a middleware that allows robotics and other real-time software to be divided into a number of processes that share data over a common publish/subscribe message architecture. By developing the required API using this framework, we expect to provide an API that uses a well-documented form and that is approachable for academic researchers. ROS provides language bindings in C++ and Python, which provides some built-in flexibility to meet researchers in their own areas of computing expertise. Although

ORSF was a significant contributor in the first budget period of this project, changes in their organizational structure and the hiring of the requisite skill-sets at MBARI led to a change in the original plan for Budget Period 2. For Budget Period 2 MBARI is providing all needed software engineering, leading to a more cost-effective effort.

Budget Period 1 of this project concentrated on building, testing, and validating the necessary software tools and is complete. Budget Period 2 is focused on marketing the result and helping users make use of the system, this is ongoing and Table 1 highlights the current status of the milestones set out in the original statement of work.

Table 1: Budget Period 2 Milestone Progress

			Completion Month	
	Milestone	Percent Completed	Scheduled	Actual
12.5.1	Attend conference or seminar	100%	36	30
14.2.1	Buoy Deployed	100%	28	28
15.2.1	Successful on-buoy use of user code	0%	33	
17.2.1	Buoy Deployed	0%	40	
18.2.1	Successful on-buoy use of user code	0%	45	

b) Accomplishments and Developments in this Reporting Period

In this reporting period the project completed the second of three buoy deployments that are included in this project as cost-shares. The deployment ended just before the planned recovery date due to a power-electronics failure for which the cause remains uncertain. Nevertheless, the buoy deployment was not significantly shorter than it otherwise would have been and the relevant electronics have since been repaired. Through the end of the reporting period and now ongoing, the system has been undergoing an extensive maintenance service. We anticipate the system will be re-deployed in March of 2025 and will remain at sea until the end of 2025. These deployments are tending to be longer than was originally planned and time-at-sea of the physical system has not been a limitation to this project. During this maintenance period, in addition to the significant repair of the power-electronics, a number of non-critical but annoying issues have been identified and addressed, improving the quality of the performance data available on the buoy. For instance, some physical wear in the wiring harness that powers the piston position sensor was identified, improving the accuracy and availability of that telemetry stream, which can be very useful for controls work.

Also in this reporting period, a paper that characterizes the performance of the simulation environment developed in this project has been published:

Dizon, Chris, Ryan Coe, Andrew Hamilton, Dominic Forbush, Michael Anderson, Ted Brekken, and Giorgio Bacelli. 2024. "Analysis on Evaluations of Monterey Bay Aquarium Research Institute's Wave Energy Converter's Field Data Using WEC-Sim and Gazebo: A Simulation Tool Comparison" *Applied Sciences* 14, no. 23: 11169. https://doi.org/10.3390/app142311169

This paper is a very useful comparison between the performance of the simulation and the performance of the measured at-sea buoy behavior. This work also includes a comparison between the mbari_wec simulator and a WecSim model of the system, this allows a phase-resolved comparison between the two models that is not possible with at-sea data. This work illustrates that both the mbari_wec simulator and the WecSim model provide a realistic representation of this wave-energy converter. Such direct comparisons between simulations and at-sea measurements are fairly rare and having this favorable result increases the credibility of the mbari_wec simulator. Not covered in the paper is the fact that the mbari_wec simulation environment developed here is considerably faster than the WecSim simulator, e.g. by several orders of magnitude. The result published in the paper indicating comparable performance at this much faster speed indicates that the design choices made during the development of mbari_wec to prioritize speed of execution have not harmed the performance of the simulator, although some of the speed gains are due to coding in C++ instead of matlab/simulink.

We have done some work to improve the documentation site for this project, adding some needed descriptions and details of the simulation environment, as well as some details about the message passing protocol used. We have added a reference to the above-mentioned paper to the documentation site as well: https://osrf.github.io/mbari_wec/main/resources/ Work to improve the documentation is ongoing.

User engagement continues to be a difficulty for the project. To help address this we have agreed to participate in the upcoming "Software Demo Days". We have been in contact with Megan Anderson at Sandia National Labs and are scheduled for a one-hour demo on Wednesday, April 30th. This online session is schedule to start at noon mountain time, and include a one-hour demo followed by a 30-minute question and answer period. We see this as a great opportunity to refine our materials that highlight the use of the software and are working now to develop a good presentation. We are hopeful this material will find use in other training activities as well.

Finally, we are excited that the Bipartisan Infrastructure Law funded activity to collaborate with faculty and researchers at the University of Washington and Oregon State University is finally able to begin. The project plans for this effort directly involve the use of the software developed in this project, and the staff involved (Jim Thompson, Brian Polayge, Merrick Haller, and Curtis Rusch) have an excellent track record of productive research and student engagement. In this reporting period we got word that the funding was secured and that work would likely begin at the start of 2025. In preparation for that we did some work in December to help with the NEPA reviews surrounding the planned activities near the MBARI WEC that include small wave-measurement buoy deployments, and drone flights. Permitting for the buoy deployments is quite easy as it's a routine activity at MBARI and covered by our ongoing permit with the Monterey Bay Marine Sanctuary. Although we also do drone activities, that permitting can be much more specific to the characteristics of the drone and the specific flight paths. For these reasons, in a recent meeting we have agreed that the personnel at Oregon State University that own and operate the relevant drones would take the lead on the drone permitting, with MBARI providing knowledge of the local regulatory environment. As stated, the small buoy deployments are straightforward and will be done under the existing permits MBARI holds, as was the case for the NEPA review of the MBARI WEC deployments for this project, this arrangement was favorably recieved.

On the technical development side for this collaboration, the requirements are fairly straightforward and include ROS 2 message support on the buoy, and an inclusion of a representation of the SWIFT wave-measurement buoys in the mbari_wec simulation. Both of these are underway and should lead to a new release of the mbari_wec simulator shortly. We have been speaking with the relevant faculty at University of Washington and Oregon State and impressing upon the requirement for graduate students they recruit as part of this project to have the necessary Linux and programming background. As we have seen before, it's hard (but not impossible) for novices to come up to speed with this software environment.

And unfortunately, recent developments in Washington have cooled progress with recruiting students and getting started with this project. On January 24th we received an e-mail from our collaborators at the University of Washington that they had received warnings to be careful in recruiting graduate students that are to be funded by Bipartisan Infrastructure Law due to communications from the government that put this funding in question. We are hopeful this concern clears quickly and we can do this project, it's a great opportunity for the mbari_wec simulation platform and the MBARI WEC itself. For our part, we have received some of the technical details needed to proceed with our (relatively small) software development effort for this project, and are doing so to be well prepared for whatever comes. In the worst case, the capabilities we are adding will be of general use in the simulator.

c) Training and Professional Development Opportunities

The planned BIL funded project with the UofW/OSU groups is the best opportunity to engage students in this project and line of work. This team has a very strong track record of successful student engagement so we are looking forward to the opportunities that may result. Additionally, Ted Brekken at OSU has indicated he has some funding for a student to get involved in some control-system development in the spring of 2025, so that is a pending possibility that will hopefully become more clear soon.

d) Results Dissemination

The open-source software development in this reporting period represents the bulk of the results dissemination as the public at large has had access throughout the development process. As described above, the wave-body interaction hydrodynamic computations used in this project have been broken out into a stand-alone library that may be useful for several outside efforts. Additionally, the publication in Applied Sciences described above is a significant dissemination of the results and capabilities of the software developed here.

e) Plans for the Next Reporting Period

We are hoping to advance the BIL project with the University of Washington and Oregon State University as aggressively as possible in this upcoming reporting period. This is our best immediate opportunity to put this system to use. Additionally, we are participating in the Software Demo Days as described, although this is officially in the subsequent reporting (April 30th), we will be developing these materials in this upcoming reporting period and will look for opportunities to disseminate. We are working to include some specific capabilities related to remote wave-detection in the system and in the simulator, and are also creating a framework for model predictive control that would take advantage of these measurements. As always we will work to improve the documentation of the system and work on outreach efforts to spur engagement.

Products

a) Publications, conference papers, and presentations:

Dizon, Chris, Ryan Coe, Andrew Hamilton, Dominic Forbush, Michael Anderson, Ted Brekken, and Giorgio Bacelli. 2024. "Analysis on Evaluations of Monterey Bay Aquarium Research Institute's Wave Energy Converter's Field Data Using WEC-Sim and Gazebo: A Simulation Tool Comparison" *Applied Sciences* 14, no. 23: 11169. https://doi.org/10.3390/app142311169

On October 18th, we presented a seminar about this project at the University of California Santa Cruz department of Electrical Engineering and Computers Science as part of the Cyber-Physical Systems Research Center.

b) Websites:

The following web-sites contain software developed by this project:

The top-level websites for the code and documentation are:
- https://github.com/osrf/mbari_wec
- https://osrf.github.io/mbari_wec/

And the constituent repositories that provide specific functionality are:
- https://github.com/osrf/mbari_wec_gz
- https://github.com/osrf/mbari_wec_utils
- https://github.com/hamilton8415/FreeSurfaceHydrodynamics

The first group of these are likely to be visited by users, and the second group by developers.

c) Technologies or Techniques

- Budget Period 1 of this project has spurred changes to the Gazebo simulation framework to properly include added-mass effects in the physics simulation and that work is now complete and available in all the most recent distributions of Gazebo. This is a necessary capability for Gazebo to be used for marine robotics. A second indirect result of this project is the stand-alone free-surface hydrodynamics library (https://github.com/hamilton8415/FreeSurfaceHydrodynamics). Although this was developed to support this project, other uses are being investigated and we hope this work can make a contribution to other projects and fields.

d) Inventions, patent applications, and/or licenses

None.

e) Other products

None.

Participants & Other Collaborating Organizations

a) Individuals

1. Name: Andrew Hamilton
2. Total Number of Months: 1
3. Project Role: PD/PI
4. Researcher Identifier: None
5. Contribution to Project: Principal Investigator and Project Manager, directs all activities.
6. State, U.S. territory, and/or country of residence: California, U.S.A.
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: Not Applicable
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay: Not Applicable

1. Name: Michael Anderson
2. Total Number of Months: 1
3. Project Role: Other Professional – MBARI Software Engineer
4. Researcher Identifier: None
5. Contribution to Project: Performs Software Engineering, Programming, and Documentation Tasks. Participates in all meetings.
6. State, U.S. territory, and/or country of residence: California, U.S.A.
7. Collaborated with individual in foreign country: No
8. Country(ies) of foreign collaborator: Not Applicable
9. Travelled to foreign country: No
10. If traveled to foreign country(ies), duration of stay: Not Applicable

b) Change in PI/Senior Personnel

None

c) Partner organizations

None

d) Other collaborators

- We have a long-standing collaboration with the Ryan Coe group at Sandia with funding independent of this project. We anticipate this project will benefit that effort and facilitate some of the goals of that partnership. Therefore, we continue to keep the Sandia group apprised of our work here and this project is benefiting from previous modelling work done by Sandia, and their expertise in general.

- We continue to develop a relationship with Ted Brekken at Oregon State University as users of this project's products. Ted has some funding to support a student and is interested in involving this project with that work, probably starting spring 2025.

- The collaborative project with Jim Thomson (UofW), Curtis Rusch (UofW), Mick Haller (OSU), and Brian Polagye (UofW) is established. This collaboration should formally start in January 2025.

- Recently, we have been in discussions with the MHKit team, it is still a bit unclear how these projects can benefit one another, but we are still exploring.

Impact

a) Impact on the principal disciplines

As part of this project we have developed a general-purpose software library that computes wave-body interaction forces for floating bodies. This is used by this project, and also available to others as it has no specific ROS/Gazebo characteristics. In the future we hope to facilitate research results in the area of wave-energy conversion device control.

b) Impact on other disciplines

This project has spurred changes to the Gazebo simulation framework to properly include added-mass effects in the physics simulation. This is a necessary capability for Gazebo to be used for marine robotics. Additionally, in the course of this project three small issues with ROS itself came to light, we fixed those and had the necessary changes accepted into the ROS 2 source-code tree.

c) Impact on development of human resources

None

d) Impact on teaching and education

None yet.

e) Impact on infrastructure

None expected.

f) Impact on technology transfer

None yet.

g) Impact on society

None.

h) Budget percentage spent in foreign countries

0%

Changes/Problems

a) Changes in approach.

b) Actual or anticipated problems or delays and actions or plans to resolve.
We continue to work towards finding appropriate users, and need to expand this some as we move forward.

c) Changes that have an impact on expenditures
None.

d) Changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents.
None and not expected to be applicable.

e) Change in primary performance site location.
None.