Project Title

Open Wave-Energy Control System Development Platform

Federal Agency and Award Number

DOE – EERE

DE-EE0009444

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Recipient Organization

Monterey Bay Aquarium Research Institute

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Project Period of Performance

10/1/2021 - 9/30/2025

Reporting Period End Date

6/30/2023

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 includes 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.

Budget Period 1 of this project concentrates on building the necessary software tools, and incorporating a few beta users into the system, using the simulation tools in the near term and for on-buoy operations in the second year of the project. Budget Period 2 is focused on marketing the result and helping users make use of the system.

Table 1: Budget Period 1 Milestone Progress

	Milestone	Percent Completed	Completion Month Scheduled	Completion Month Actual
1.7.1	ROS Running on MBARI WEC Computer	100%	6	5
2.2.1	Simulator selected	100%	5	5
2.8.1	Simulator integrated	100%	8	12
3.4.1	All software packages are published publicly	100%	9	18
4.3.1	MBARI control running in ROS system	100%	9	5
5.3.1	Portal ready to launch	100%	9	20
6.2.1	Webinar completed	100%	11	20
7.2.1	Buoy Deployed	100%	16	17
8.2.1	Successful on-buoy use of user code	50%	21	
9.1.1	Workshop or online training completed	0%	16	

b) Accomplishments and Developments in this Reporting Period

The simulation environment was completed to a releasable form in this reporting period, this result can be accessed at the links in the “Products/Websites” section below. As part of that release, a discussion forum has been formed with an announcement and invitation for participation. This is a significant step for the project, and we are looking forward to outside engagement, and the opportunity to refine the product based on feedback from individuals that have not yet been involved. As described in the goals for this project above, this simulator aims to be a digital twin for the physical system, and we believe that we have included all relevant features. Naturally there are some items such as detailed status messages that are not practical to simulate, but we believe that we have included all relevant physical behaviors.

The resulting simulator has demonstrated excellent stability and runtime efficiently, running as fast as 50 times faster than real-time (this naturally depends on the computer infrastructure being used). This fast operation was a design goal of the system and opens up the possibility of examining a large number of possible control configurations across a range of sea-states. The design choices made mean that the internal working of this simulator is different in some areas compared to the WecSIM model that the Sandia group created for this system. As noted previously, these two models are providing different predictions for the WEC behavior when supplied the same input parameters. This is somewhat expected, and we continue to work to identify the exact cause of the discrepancy. We believe this is related to how the systems friction loss components are being handled, and our baseline for these comparisons is the performance of the at-sea system which of course has features that are unmodelled in both simulators. This project continues to collaborate with Chris Dizon at Oregon State University to investigate and characterize these behaviors, and he has begun running the simulator for this project alongside WecSIM. The desire to compare to at-sea data makes this a fairly sophisticated analysis. We do not believe the cause of the differences is a fundamental issue with either simulator, but rather related to how friction loss components are being included, a very tricky detail to get correct in any simulator as it can be a very nonlinear phenomenon. It is not our view that these discrepancies are a hindrance to the intended use of the simulator at this time, although it would be nice to understand their origin and correct for them in time if possible. We expect to co-author a paper with Chris Dizon that addresses these issues.

Throughout this reporting period, the MBARI WEC itself has been deployed in Monterey Bay in what is one of our most successful deployments to date (and a cost-share task in this project). During this deployment the ROS software developed in this project has been executing on the buoy computer, and is used to implement some of the behaviors the system relies upon. In particular in this deployment we have made progress on a previously limiting item related to how the main tether was wearing due to friction. An inspection dive in May indicated a significant reduction in wear for this item, and we are scheduled for a repeat dive to further evaluate the total lifetime of this component. Interestingly, the friction resulting in the wear of the tether jacket is the primary candidate for an un-modelled loss that may be contributing to the model versus at-sea data discrepancies. Reducing this friction and wear in the system is a very positive development for the physical system, but is complicating the simulation comparisons. The power generating characteristics of the system appear to have improved compared to previous deployments, indicating a change of friction in that component which means that we would not expect the simulator to match this and previous deployments without adjustments. We anticipate leaving the buoy on-site into November, and bringing the system in for inspection this winter to prepare for the 2024 deployment which is also included as a task in this project. The extended deployment durations we are achieving benefit this project by providing significantly more time at sea for the system. Figure 1 shows some high-level performance data for this deployment, the system has spent most of this deployment operating in a de-tuned manner due to the failure of a non-critical system sensor early in the deployment. This item will be repaired in the upcoming maintenance period.

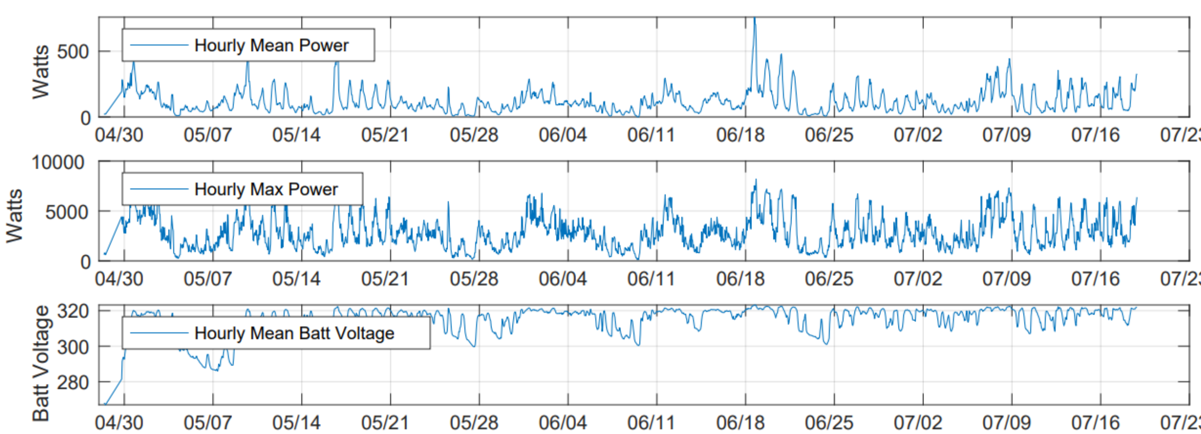

Figure 1: Summary data from 2023 MBARI WEC deployment in Monterey Bay.

Although slower than we would like, we are gaining some traction with engaging outside collaborators in the use of this software. We have continued to speak about this project in a variety of venues, with more planned. In particular, in addition to seminars at UofW/APL and Johns Hopkins University in previous reporting periods, Hamilton presented this project at Woods Hole Oceanographic Institution on April 3rd, 2023. On June 28th, we had a one-on-one discussion with PhD candidate Brittany Lydon about her interests in using this platform. That discussion and our previous outreach at UofW has led to a collection of faculties at UofW and Oregon State to submit a project proposal to PMEC to use this platform over the next years. Those faculty are Jim Thompson (UofW), Brian Polyage (OSU), Mick Haller (OSU), and PostDoc Curtis Rusch (UofW). We have experience with all of these individuals and will be very pleased if this group puts this system into use. The project is structured to involve several PhD students over the coming years. Submission of this project proposal occurred after the end of this reporting period, but we felt it was noteworthy and hope to report on a positive outcome in the next report. Similarly, as discussed above, Chris Dizon at Oregon State University is becoming a user of the system.

As previously discussed, the end of Budget Period 1 is fast approaching (9/30/2023) and we are behind on a few milestones as illustrated in the table above. In particular we had planned to have outside users more engaged in the project at this stage, but delays getting started, changes of staff and ownership at Open Robotics, and the general complexity of the project has kept us from completing milestones related to outside use of the system, and on-line training activities we had planned. As also previously discussed, a no-cost extension to budget period one may be a sensible approach to solving these problems and we would like to discuss the specifics of this. In addition to allowing us to complete the tasks planned, a delay now would allow this project to align better with the PMEC project timeline should that funding be secured.

The ownership change at Open Robotics has continued to be a significant problem, and at this point our recommendation will be to not engage this outfit as a sub-award in budget period 2. The necessary expertise now exists within MBARI and we would perform the efforts previously planned to be outsourced in-house. This will entail a rather significant change in the budget specifics, but not a change in total amount or cost share.

c) Training and Professional Development Opportunities

Post-doctoral fellow Chris Dizon at Oregon State University (under Professor Ted Brekken) continues to work with the MBARI and Sandia Engineering teams. Currently Chris is working to compare some of the at-sea results with the model predictions of the WEC-Sim model of the MBARI system, and has begun to run the simulator from this project.

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.

We continue to pursue opportunities to speak in public about this project and generate interest among potential users. On April 3rd of this reporting period, Andrew Hamilton presented this project at Woods Hole

Oceanographic Institution as part of the design study meeting that is investigating the application of Wave Energy in the NSF funded Ocean Observing Initiative.

e) Plans for the Next Reporting Period

In the next reporting period we plan to support the released software and encourage use from the community. We have established a discussion forum and are working to be as responsive as possible to questions and requests. As an example, we have received a request to make some of our existing Matlab post-processing tools available, and are currently developing a tutorial for those and adding them to the code repository. This and similar efforts should make the system easier to use. We also plan to expand the comparison of simulator to at-sea results to include a comparison to the 2023 deployment, the apparent tether drag change in this deployment may provide us a second data point and allow us to tune some of the un-modelled losses in the system. Similarly, the plans of the UofW/OSU group include a need for the simulator to provide wave-elevation data at arbitrary locations and time. This resporting is not in the simulator at this time but will be straightforward to add, as we anticipate this to be a useful feature in general, we will work to add this before the UofW/OSU work becomes finalized. We will also of course be working towards the final incomplete milestones listed above and are working to determine the best way to perform an on-line training.

Products

a) Publications, conference papers, and presentations:

- On April 3rd of this reporting period, Andrew Hamilton presented this project at the Woods Hole Oceanographic Institute.
- In this reporting period we submitted a proposal to present this project at ROSCon in October, 2023. We anticipate this proposal will be accepted and we will be added to the schedule of talks at that conference.

b) Websites:

The names of the GitHub repositories that make up the bulk of this project have changed from our working titles to more descriptive names. As a result, the various websites that contain the project output.
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

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.

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: 2
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: 3
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

1. Name: Mabel Zhang
2. Total Number of Months: 1
3. Project Role: Other Professional – ORSF PD/Software Engineer
4. Researcher Identifier: None
5. Contribution to Project: Leads Open Robotics activities
6. State, U.S. territory, and/or country of residence: Boston, MA, 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: Dharini Dutia
2. Total Number of Months: 2
3. Project Role: Other Professional – ORSF Software Engineer
4. Researcher Identifier: None
5. Contribution to Project: Software engineering and programming
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: Vanessa Yamzon Orsi
2. Total Number of Months: .1
3. Project Role: Other Professional – Co PD/PI
4. Researcher Identifier: None
5. Contribution to Project: CO-PI and project oversight
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

Due to the changes related to the sale of Open Robotics to Intrinsic, Vanessa Yamzon Orsi has taken over as the PI for the Open Robotics subaward. Her role is purely administrative and she has not engaged in the technical components of this project.

c) Partner organizations

1. Open Robotics Software Corporation.
2. Mountain View, CA USA.
3. Partner's contribution to the project is Collaborative research and In-kind support.
4. Open Robotics Software Foundation is a domestic organization that that supports all administrative and technical development of ROS, ROS2 and the associated Gazebo simulator. These open-source projects form the software basis for most of this project. Having this organization as an official subaward on this project provides access to expertise and best-practices for these software products. This is allowing this project to produce a professionally developed product that will be maintainable and suitable for inclusion in the larger ecosystem of ROS and Gazebo software.

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 and Chris Dizon at Oregon State University as users of this project's products.

- Rhys Mainwaring has been collaborating with this project as an outlet for his wave-body interaction developments for Gazebo. Rhys is making significant contributions to this effort and we are working to balance those contributions with a desire to not become dependent on work we have little control over.

- We have had been speaking with Brittany Lydon who is a PhD candidate at the University of Washington (Polagye lab). Brittany has expressed interested in using this platform and we are encouraging and helping her get started. At this she is interested for her own research interests, and she may become involved in the UofW/OSU/PMEC project depending on how her career develops.

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. Nothing else yet. 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.
None.

b) Actual or anticipated problems or delays and actions or plans to resolve.
Simulator development continues to lag the original planned schedule. This is due to both the complexity of the task, and the delay in getting the Open Robotics subaward in place at the beginning of the project.

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.

Appendix A: WBS for Budget Period 1.

Green indicates completed.

Black indicates still to be done.

				PROJECT TITLE	**Open Wave-Energy Control System Development Platform**		
				Recipient Name	MBARI		
				Project Start Date	11/1/2021		
				Project End Date	10/30/2025		
Budget Period #	**Task Type**	**Task #**	**Subtask #**	**M or D #**	**Milestone/Deliverable Description**	**Planned Project Month START**	**Planned Project Month END/DUE**
1…10	*Select*	*0…50*		*0…n 0.0…n*	*Title text from SOPO*	*1…120*	*1…120*
1	T	1	0	0	ROS integration into buoy controller	1	6
1	ST	1	1	0	System architecture planning	1	2
1	ST	1	2	0	Create ROS Package defining message data structures	3	5
1	ST	1	3	0	Create ROS package that publishes CANbus data	3	5
1	ST	1	4	0	Create ROS package that publishes AHRS/GPS data	3	5
1	ST	1	5	0	Create ROS package that logs data on the buoy	3	5
1	ST	1	6	0	Create ROS package that provides streaming telemetry	3	5
1	ST	1	7	0	Test on Buoy Computer	6	6
1	M	1	7	1	ROS Running on MBARI WEC Computer	6	6
1	T	2	0	0	Integrate wave-energy simulator into ROS environment	3	8
1	ST	2	1	0	Planning	3	4
1	ST	2	2	0	Evaluate simulation tools	4	4
1	M	2	2	1	Simulator selected	5	5
1	ST	2	3	0	Integrate selected simulation into ROS package	4	5
1	ST	2	4	0	PTO and power system simulation	4	5
1	ST	2	5	0	Implement Heave Cone simulation	4	4

1	ST	2	6	0	Develop Simulation Inputs	5	7
1	ST	2	7	0	Develop visualization tools	4	7
1	ST	2	8	0	Test code interoperability with buoy hardware	7	8
1	M	2	8	1	Simulator integrated	8	8
1	T	3	0	0	**Publish Simulated Environment**	8	9
1	ST	3	1	0	Publicly release software from task 1 and 2	8	9
1	ST	3	2	0	Create example tutorial	8	9
1	ST	3	3	0	Test example tutorial	8	9
1	ST	3	4	0	Export example tutorial to website/portal	8	9
1	M	3	4	1	All packages are published publicly	9	9
1	T	4	0	0	**Port existing MBARI control to ROS system**	6	9
1	ST	4	1	0	Transfer current logging and control features to ROS system	6	8
1	ST	4	2	0	Transfer current system control features to ROS system	6	8
1	ST	4	3	0	Run standard performance/logging tests with ROS system	8	9
1	M	4	3	1	MBARI control running in ROS system	9	9
1	T	5	0	0	**Develop website/portal for user access/outreach**	7	9
1	ST	5	1	0	Planning and toolchain selection	7	7
1	ST	5	2	0	Establish communication channel for online community	7	8
1	ST	5	3	0	Create website entry-point	8	9
1	M	5	3	1	Portal ready to launch	9	9
1	T	6	0	0	**Launch of simulation capabilities to beta group**	9	15
1	ST	6	1	0	Planning and identification of beta users	9	9
1	ST	6	2	0	Prepare and hold webinar	9	10
1	M	6	2	1	Webinar completed	11	11
1	ST	6	3	0	User Support	10	15
1	ST	6	4	0	Website and data management	10	15
1	ST	6	5	0	Results review	12	15
1	T	7	0	0	**Buoy deployment, recovery and maintenance #1**	15	21
1	ST	7	1	0	Pre-deployment assembly and test	15	16
1	ST	7	2	0	Deployment	15	16

1	M	7	2	1	Buoy deployed	16	16
1	ST	7	3	0	At-sea monitoring	16	21
1	ST	7	4	0	Recovery, cleaning and refurbishment	21	21
1	T	8	0	0	**Support of on-buoy operations for beta group**	17	21
1	ST	8	1	0	Safety review of controller behaviors in simulation	17	17
1	ST	8	2	0	User support during on-buoy operations	17	21
1	M	8	2	1	Successful on-buoy use of user code	21	21
1	ST	8	3	0	Data management	17	21
1	ST	8	4	0	Assistance with results analysis and publication	20	21
1	T	9	0	0	**Marketing and outreach**	13	24
1	ST	9	1	0	Documentation and workshop or online training preparation	13	15
1	M	9	1	1	Workshop or online training completed	16	16
1	ST	9	2	0	Advertising	13	24
1	ST	9	3	0	Website/portal maintenance	13	24
1	ST	9	4	0	Workshop or online training	18	18
1	ST	9	5	0	Conference attendance	13	24
1	ST	9	6	0	Coordination with MERC	13	24
1	T	10	0	0	**Support of simulation capabilities for all interested parties**	15	24
1	ST	10	1	0	User support	15	24
1	ST	10	2	0	Code maintenance	15	24
1	ST	10	3	0	Results review	15	24
1	T	11	0	0	**Go/No-Go Review**	20	24