Project Title

Open Wave-Energy Control System Development Platform

Federal Agency and Award Number

DOE – EERE

DE-EE0009444

Principal Investigator Contact Info

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Recipient Organization

Monterey Bay Aquarium Research Institute

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DUNS Number

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Project Period of Performance

10/1/2021 - 9/30/2025

Reporting Period End Date

12/31/2022

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 critical and 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

			Completion Month	
	Milestone	Percent Completed	Scheduled	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	90%	8	
3.4.1	All software packages are published publicly	90%	9	
4.3.1	MBARI control running in ROS system	100%	9	5
5.3.1	Portal ready to launch	90%	9	
6.2.1	Webinar completed	0%	11	
7.2.1	Buoy Deployed	0%	16	
8.2.1	Successful on-buoy use of user code	0%	21	
9.1.1	Workshop or online training completed	0%	16	

b) Accomplishments in this Reporting Period

This reporting period has included considerable development work on the simulation environment, and some marketing and outreach activities. As always, as the completion of a software development project gets closer, progress through a myriad of details seems to get slower, and this project is no exception. Nevertheless, we are making progress and while a little bit behind the original schedule, we do expect to have a viable and documented simulation environment for this project available soon.

Some organizational changes are occurring at our partner Open Robotics, and this has had an impact on our progress. In particular, Open Robotics has been acquired by Intrinsic (https://intrinsic.ai/), a subsidiary of Google. Some details are in this blog post from Open Robotics CEO Brian Gerkey: https://www.openrobotics.org/blog/2022/12/15/intrinsic-acquires-osrc-and-osrc-sg. This occurred in December 2022, and has resulted in some personnel changes of Open Robotics staff working on this project, these are detailed in the "Participants & Other Collaborating Organizations" section below. In the immediate term, Open Robotics has committed to continuing support for this project and honor the sub-award we have in place with them. It should be noted however, that Intrinsic has their own priorities in buying this company that are almost certainly not related to providing software-development consulting services. The subaward for this project was structured following a BP1 and BP2 structure, so it is yet to be seen if we will have the same access to Open Robotics staff in BP2.

Fortunately, we have gotten most everything we really needed from Open Robotics in the first year of this project. In particular, the additional features that we needed in the Gazebo simulator are complete and integrated into the released versions of the software. The remaining work we really need from Open Robotics is more support oriented and less software development. If the amount of time they are able to commit to this project in BP2 reduces, we will be able to proceed with all of the original plans. We expect this to be negotiated at the time the BP2 sub-awards are negotiated and a possible outcome is that some of the funds originally allocated to Open Robotics will need to be re-allocated to MBARI engineers.

In this reporting period, there has been the finalization of a number of specific features of the simulator and the system is currently undergoing the final integration of tests of these features into a complete system.

- As discussed previously, a significant addition has been made to the Gazebo simulator to now treat added-mass forces correctly, allowing the simulation of submerged bodies. This feature is now available in the latest release of Gazebo (Garden), in both the source-code release as well as the easier to install binary distribution of the software.
- All software developed in this project has now been upgraded to use the latest version of Gazebo (Garden), so the added-mass features are now being used by this project.
- Wave-body interaction forces have been added to this project's capability, allowing the simulation of floating bodies that respond to surface-waves based upon the usual linearized free-surface wave-body hydrodynamics formulation. As previously discussed, this project has attracted the attention of Rhys Mainwaring, who is independently developing Gazebo simulator plugins related to wave-body interactions (srmainwaring/asv). Rhys is focused largely on the buoyancy and wave-excitation forces and in particular the inclusion of non-linear contributions. This is excellent and important work that we hope to make use of, but for this project specifically we have implemented the linearized versions as per our original plan. This has been completed in this reporting period and is undergoing integration into the simulator now. The intent here is to ensure we have a solution for this important forcing that isn't dependent upon an outside contributor, while at the same time making use of work done by others. Additionally, there are some elements of the work performed by this project that will be useful for Rhys and others. For that reason, the linearized wave-body interaction computations have been broken out of the Gazebo-oriented software and now exist as an independent library (https://github.com/hamilton8415/FreeSurfaceHydrodynamics). This library is currently being used by this project's Gazebo simulator, and by being separate will also be usable by others. In particular we have been in communication with Dave Ogden on this and there may be some cross-over from this code into his Chronos efforts. All of this was recently discussed at the Gazebo Marine Robotics Community Meeting, a recording of that meeting is viewable here: (https://drive.google.com/file/d/1BM4brnvAjDNsIKPMuZsxUTza0koTvanH/view).
- Documentation continues to be developed and is visible here: (https://osrf.github.io/buoy_entrypoint/pr-preview/pr-17/). The aim for this documentation is to describe the intent and operation of the system, provide a complete series of tutorials that will guide a new user through installation and use of the system, and document the characteristics of the system to the level a researcher would need to understand its performance.

The current state of the simulator code, examples and documentation are available at the following repositories on GitHub:

- https://github.com/osrf/buoy_entrypoint
- https://github.com/osrf/buoy_msgs
- https://github.com/osrf/buoy_sim

Although most of the effort in this reporting period has been concentrated on software development, there have been some outreach activities as well. In particular, PI Hamilton presented an overview of this project at the IEC US TAG – TC 114 annual meeting in Santa Cruz, CA on November 17th, 2023. Hamilton also travelled to both Iowa State University and Johns Hopkins University and spoke about this project at each location. On November 28th, Hamilton joined the lab meeting of Ossama Abdelkhalik at Iowa State and gave a short presentation on this project to graduate students Mohamed Shabara, Habeebullah Abdulkadir and Benjamin Jones. This is a group that is active in wave-energy controls research and so may have an interest in this project as it matures. On December 6th, Hamilton presented an invited seminar at Johns Hopkins University, hosted by Umesh Korde. About half of that seminar contained material from this project, and resulted in ongoing discussions with Prof. Louis Whitcomb and his student Nivya Kuzhivila Pannickottu. Louis Whitcomb is a roboticist of some renown and his involvement in this project would carry considerable weight so we were pleased to make this connection. In each case the relative immaturity of our software platform at the moment became a bit evident as these researchers tried to download and use the work, this has reinforced our resolve to refine this system to a predictable state in which all the tutorials and behaviors work as expected. In the meantime we are working to support these early users personally to keep them engaged.

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 he is working to compare some of the at-sea results with the model predictions of the WEC-Sim model of the MBARI system. In fact, once the simulation environment is complete, an important task will be to perform some comparisons with our at-sea test data, and produce an academic style paper characterizing the performance. It is possible Chris' work will contribute to this.

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.

e) Plans for the Next Reporting Period

We continue to work to get this software into a completed state, and again aim to have a complete version of the code and documentation available in the next reporting period. There may be features to improve or add at that point, but we want to be sure we develop a minimum viable product before we expend additional efforts on details and refinements. Additionally, outreach efforts will continue to ramp up, and plans for the summer 2023 at-sea buoy deployment will be refined. In particular, we have been invited to present details of this project at the next Gazebo Marine-Robotics Community meeting, and MBARI engineer Michael Anderson is planning to make that presentation.

Products

a) Publications, conference papers, and presentations:

- On November 17th, 2022, a presentation about this project was made at the IEC US TAG – TC 114 annual meeting in Santa Cruz, CA.
- On December 6th, 2022, this project was presented at an invited seminar at Johns Hopkins University.

b) Websites:

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

- https://github.com/osrf/buoy_entrypoint
- https://github.com/osrf/buoy_msgs
- https://github.com/osrf/buoy_sim
- https://github.com/hamilton8415/FreeSurfaceHydrodynamics

Documentation is available here:

- https://osrf.github.io/buoy_entrypoint/pr-preview/pr-17/

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

During this past reporting period, a staff at Open Robotics has been re-organized in the wake of the acquisition of that company by Intrinsic, a Google subsidiary. As a result, Michael Carrol has been re-assigned and Mabel Zhang has stepped in as the project manager for the subaward this project has with Open Robotics. This is the second project manager change we've endured, and each time there has been a productivity cost as the new person comes up to speed, but we are working through that and all signs are that Open Robotics will be able to continue to produce for the project. Additionally, as part of the change, Joan Mayans is no longer with Open Robotics/Intrinsic, Joan had done some important work for us related to the added-mass addition, but most of that work is completed so we should be able to proceed without him. The names list below reflect the addition of Mabel, Michael and Joan continue to appear on the list as they did contribute in the reporting period.

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: Rob McEwen
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

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: Michael Carrol
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: 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: Joan Mayans
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: 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: 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: Tully Foote
2. Total Number of Months: .25
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

None.

c) Partner organizations

1. Open Robotics Software Foundation.
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 possible 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.

Impact

a) Impact on the principal disciplines
None 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 ROS2 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 actors 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. We are working hard now to get this simulator to a basic completeness, at the expense of every feature we would ultimately like to include, but those features can be added later.

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 in previous reporting periods.

Red indicates completed in this reporting period.

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