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

3/31/2022

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 easily 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 the 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 also 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	90%	6	
2.2.1	Simulator selected	100%	5	5
2.8.1	Simulator integrated	10%	8	
3.4.1	All software packages are published publicly	0%	9	
4.3.1	MBARI control running in ROS system	100%	9	5
5.3.1	Portal ready to launch	0%	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

In this reporting period, the project has made progress on all three of the main areas of the project; ROS integration into the MBARI WEC, Simulator Development, and outreach and user engagement. Progress and accomplishments in the three areas are described below.

<u>Buoy Software Infrastructure</u>

This component of the effort was largely completed in this reporting period and ROS is currently running on the buoy computer. Appropriate ROS messages have been defined and code has been written that allows the buoy Linux computer to publish all the buoy telemetry data on ROS topics. Additionally, ROS services have been created that allow ROS code to issue commands to the buoy hardware. Both of these tasks were facilitated by considerable code-use of software that had been previously developed for MBARI uses on the buoy. This is not inappropriate and presents no limitations to current and future plans. A benefit from this choice is that we are leveraging some highly reliable existing code, instead of re-implementing certain features. The ROS message descriptions and example code that demonstrates the use of this software have been collected in typical ROS packages and will be available publicly shortly. There is some documentation and tutorial work still to do on this, but we have tested these features thoroughly and successfully on our lab-based test-machine that exercises the MBARI WEC system in its entirety. This implementation required a change of Linux computer on the MBARI WEC, the Technologics single board computer previously being used is a 32bit ARM processor that did not have Tier 1 support for ROS. We have upgraded to a Raspberry Pi4 64bit ARM processor that has mature and ongoing ROS support. This computer is meeting our current requirements but we are also doing some investigation into more powerful computers such as the NVIDIA series of single-board computers that integrate GPU processing capabilities in low-powered computers desired for machine learning in power-constrained environments. Pairing these computers with ROS is a common occurrence and easily within the electrical power budget of the MBARI WEC, so in the future is a path to provide significantly more computing power on the buoy to support this project.

Note, we are actually using ROS2 which is rapidly taking over as the standard, the original ROS software is fading in use so we will use the term ROS to describe our work here for simplicity, but are actually referring to the improved ROS2 software.

Simulator Development

Due to staffing constraints at Open Robotics and the time it took to get the sub-award in place, Open Robotics only joined the effort in the last part of this reporting period. Therefore, actual code development on the simulator component of the project got a slightly late start. We had an initial on-line meeting at the end of February, but this was in fact slightly before the sub-award was in place. We then had a much more significant kick-off meeting on March 31st, in which Open Robotics spent the day at MBARI and we reviewed the hardware set-up and had technical discussions about the approach to be taken. This sub-award is now in place, the delay in getting Open Robotics software engineers committed to the effort did allow the project plan at MBARI to mature some, with considerable planning and requirements definition done in this period. This was a net positive in the end and has allowed rapid progress since.

A critical decision to be made in this project is the choice of software infrastructure to implement the needed simulation environment. As described above, the hard requirement is that code developed against the simulator runs un-changed on the buoy hardware. In other words, user control code should not be able to tell if it running in the simulated environment or on the real WEC. There are a number of approaches to achieve this, and the selection made now will have a significant impact on this project for the foreseeable future. Due to the involvement of Open Robotics the most attractive approach is to use the Gazebo simulator tool (https://gazebosim.org/home). This simulator is also supported by Open Robotics (along with ROS) and this is a routine pairing. Other options considered are the DOE's own WEC-SIM, for which a model of the MBARI WEC has already been developed for another purpose.

Investigations in this reporting period concentrated heavily on the trade-offs between these and other options, and we have decided that Gazebo is the appropriate choice to pursue. Although Gazebo has several advantages, there are two limitations that needed to be understood before settling on this choice. The first is that the physic engines used by Gazebo were designed to model terrestrial objects in which the object densities are much higher than the surrounding air. When these techniques are used underwater there are inertial forcing terms due to the surrounding water that are important. There are work-arounds available to include these forces, but these also introduce accuracy and stability issues in the simulation. The correct solution is to make some relatively minor changes to the base Gazebo software, and Open Robotics have identified this as possible within the scope of this project so we expect this limitation to be removed. There is a growing marine robotics community using Gazebo for simulation purposes, so this is an example of work done in this project that will have a wider impact due to the open source nature of Gazebo. The second limitation of Gazebo is a relatively rudimentary ordinary differential equation solver that is used to advance the numerical solution. This is not a fundamental problem but may limit the speed at which simulations can ultimately run for a given accuracy, and the Gazebo team has plans to address this shortcoming at some point in the future. In any event, to implement this simulator, some additional Gazebo plugin code will need to be written specific to the wave-energy converter problem, and this will result in new open-source code being added to the Gazebo software package.

WEC-Sim was also considered for this application, and in fact a WEC-Sim model of the MBARI system already exists. Although it is possible to add facilities for this simulation to publish and respond to ROS messages, two significant limitations would still remain with this approach. The first is the high cost of the necessary Mathworks toolboxes to run this simulator. This can be 10's of thousands of dollars and while many academic institutions have access to what's required, this cost will almost certainly be a roadblock to some of the target audience of this project. Additionally, simulations performed in WEC-Sim of the MBARI system run one or two orders of magnitude slower than what we expect will be achievable with Gazebo. The advantages of the WEC-Sim approach is the availability of more sophisticated numerical integration capabilities of Simulink, and the support for multi-physics processes that can be challenging to mimic in Gazebo.

After investigation, the decision has been reached to pursue a native Gazebo simulation environment for this project. At the close of this reporting period, sufficient prototyping with this software platform has been performed to allow us to reach this conclusion with confidence. Because this code will be written in C++, the execution speed advantages are significant, the result will be entirely free to use, and the involvement of Open Robotics in this project increases the likelihood that work done in this project will benefit the larger marine robotics community. Because a WEC-Sim model of the MBARI system already exists, this decision does not preclude integrating that simulation with ROS at some point, potentially resulting in a higher fidelity simulation, that would run at a significant dollar and run-time cost. At this time however, efforts are being directed towards bringing the Gazebo simulator to fruition.

Marketing and Outreach

Most of the effort in this reporting period was oriented toward internal project developments, so only limited outreach activities have occurred as opportunities present themselves, in particular:

- In response to a conference solicitation by Ryan Coe and Jeffrey Scruggs for a wave-energy session at the ***16th International Conference on Motion and Vibration Control (MoViC 2022)**,* we have had an abstract accepted for this meeting to take place at UCLA this fall. The abstract itself is in Appendix B of this report and is oriented to introducing this project and opportunities to collaborate to the traditional wave-energy research community.
- As a result of an unrelated visit to MBARI by the head of Chief of Naval Research (RADM Selby), we have been in contact with Professor Andrew Gish at the US Naval Academy. Professor Gish has some marine hydrokinetic interests and while we have not had an opportunity to have detailed discussions, but are hopeful this may be a good outlet for this project in both a research and academic setting.

c) Training and Professional Development Opportunities

With Sandia National Lab support, we have been working with Ted Brekken at Oregon State University to put in place support for a post-doctoral fellow in his lab. A candidate (Chris Dizon) has been selected and visited MBARI to gain familiarity with the system recently. The vision of this fellowship is that Chris will be a supported user of the software system that this project creates, performing wave-energy converter research and providing a training and professional development opportunity for a young researcher.

d) Results Dissemination

All work in this reporting period was performed internally, and therefore no results dissemination has occurred yet:

e) Plans for the next reporting Period

Work in the next reporting period will be almost entirely dedicated to developing the necessary Gazebo simulator software for this project. The team is in place and many of the critical decisions have been made, so we expect progress on tasks 2 and 3.

Products

a) Publications, conference papers, and presentations:

- An abstract has been accepted at the *9th IFAC Symposium on Mechatronic Systems (Mechatronics 2022)* and the ***16th International Conference on Motion and Vibration Control (MoViC 2022)***. This is a Ryan Coe organized sub-meeting with an emphasis on wave-energy. These meetings are to take place September 7-9 at UCLA in Los Angeles. (See Appendix B for the presentation abstract). The project PI will attend this conference and make a presentation on this project as an outreach and marketing activity.

b) Websites:

None yet, we have started planning for the code and documentation hosting websites and will have some materials up in the next reporting period.

c) Technologies or Techniques

None yet, in planning the simulation work for this project we have identified a technical deficiency in the Gazebo simulator code-base that limits its applicability to under-water entities. We are working as part of this project to correct this omission and we expect this technique to be immediately incorporated in the base Gazebo simulator and further the applicability of this tool for general marine and underwater simulation needs.

d) Inventions, patent applications, and/or licenses

None.

e) Other products

None yet, some components of the simulator features we are developing for Gazebo will have general applicability so we are developing these in a manner consistent with Gazebo to facilitate subsequent incorporation into unrelated projects under the open-source license Gazebo uses (Apache-2).

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: Rich Henthorn
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: Louise Poubel
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 Activies

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: 1
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

Since the time the project award was made, Michael Anderson has joined MBARI and brings significant ROS experience so is playing a large role in this project, representing a shift in hours originally allocated to other MBARI software engineering resources. These other individuals (such as Rich Henthorn) are still involved, but at a reduced scale than originally envisioned in order to take advantage of Michael's specific expertise.

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.

- In this reporting period we worked with Sandia National Labs to provide funding to a Post-Doctoral fellow in the lab of Prof. Ted Brekken at Oregon State University. This is an excellent chance to have a funded user of this system and benefit from Prof. Brekken's expertise. We anticipate further interactions with this group as part of this project in subsequent reporting periods.

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
None yet, as a side effect of this project we do hope to impact the general field of marine robotics by introducing new capabilities to the existing Gazebo simulation environment.

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.
This project was a bit slow getting started after the award was made, mostly due to staffing constraints and the time it took to get the Open Robotics Subaward in place. However, the project is quickly making up time and is essentially on schedule now.

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

Appendix B: Abstract for presentation at MoVic 2022, Sept 7-9, UCLA.

Open Wave-Energy Control System Development Platform

Andrew Hamilton, MBARI

The Monterey Bay Aquarium Research Institute (MBARI), the Open Source Robotics Foundation (OSRF), and the US Department of Energy have recently teamed up to make the small-scale wave-energy converter developed by MBARI available to the external community of wave-energy control systems researchers. The MBARI WEC is a small point absorber design that is routinely deployed in Monterey Bay and generates average powers of 250W in its current configuration. This WEC is heavily instrumented and includes a four-quadrant electro-hydraulic power take-off device, on-board battery storage, on-board computing infrastructure, and an always-on link to the internet. To date, advanced controls have not been developed or implemented for this system, and the 250W average power values that are realized result from a simple linear-damping control law. This project is implementing an Application Programming Interface (API) based on the popular open source Robotics Operating System (ROS2). This software infrastructure provides a means for third-party software running on the buoy to have real-time access to all data telemetry from the system, and take control of the target PTO forces and other items in the system that are under software control. The aim of this project is to develop and document this API to the point where wave-energy control researchers from organizations outside of MBARI can develop algorithms and run code on the MBARI WEC during at-sea deployments. The architecture of the MBARI WEC has fail-safe features that provide the necessary device security to allow this. To facilitate code development and test, a dedicated software simulator is also under development that candidate software can be tested against. The aim is that the simulator is a software facsimile of the WEC such that candidate software can run unchanged on the real buoy after running against the simulator. This talk will highlight the technical implementation of the MBARI WEC and control system API developed for this effort. The numerical model and resulting simulation environment will be described and details about how external groups can implement algorithms for this system, and then exercise them during our test deployments will be described.