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

178341772

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Project Period of Performance

10/1/2021 - 9/30/2025

Reporting Period End Date

3/31/2023

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 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	20%	16	19
8.2.1	Successful on-buoy use of user code	30%	21	
9.1.1	Workshop or online training completed	0%	16	

b) Accomplishments and Developments in this Reporting Period

Most of this reporting period has been spent completing the simulation environment, and we are experiencing the effect of how time-consuming it is to complete this sort of software development and get everything ready for an official release. The original project schedule and plan included the completion of this simulator and some initial use by outside collaborators in Budget Period 1, with maintenance of the software and expanded use of the system in Budget Period 2. Due to delays getting the project started, and the large amount of work involved in developing this simulator, it is developing that Budget Period 1 will really be dedicated to the simulator development and some internal use and Budget Period 2 will see more efforts to engage outside users. We are using the results of this project internally and with our Sandia Collaborators for some purposes, but the engagement of researchers external to MBARI is likely going to need to wait for Budget Period two to allow us to release a solid and reliable software product. We feel this extra time is important as releasing software with problems is likely to alienate potential users fairly quickly.

In any case, we have continued to speak about this project in public to generate general interest. In particular Hamilton spoke of this project at an invited seminar at University of Washington/APL on March 17th , and MBARI software engineer Michael Anderson presented the project at the ROS/Gazebo Maritime Robotics Community meeting on February 22nd. Both of these presentation were well received and generated some interest, but we still are limited by a not-quite-complete product, although we are pointing potential users to the nearly complete documentation site at: https://osrf.github.io/mbari_wec/. Note that the project name has changed from the working title of "buoy" to a more descriptive "mbari_wec", and the various repositories have followed suit as described below. We are planning further outreach efforts, with the next planned opportunity to be an online seminar for UMERC on July 16th.

This project continues to deal with the fallout from the sale of Open Robotics to Intrinsic at the end of 2022. In particular, billings have become a problem as the new company neglected to send invoices for most of 2023 so far. Additionally, the project has a sub-award with Open Robotics, not Intrinsic, so it's taken some time to resolve this. We have learned that at the time of the company sale, an agreement was put into place in which Open Robotics continues to exist as an entity through June of 2023, so we believe we can continue to receive invoices related to the original sub-award through that. In this arrangement Open Robotics is contracting out the actual work under their agreement to the original technical contributors, who now work for Intrinsic. Unfortunately, Intrinsic is still not able to say with confidence that they will accept a sub-award for the work planned in Budget Period 2, so there is uncertainty there. With that in mind, our suggested path here is to complete the planned work with Open Robotics by the end of June 2023, so we can avoid a re sub-award to the new company for the relatively small amount of remaining work in Budget Period 1. Then, at the start of Budget Period 2, we will enter into a new sub-award with Intrinsic if they are willing, if they are not, we believe we can support this project internally at MBARI and would adjust the Budget Period project plan and budget at that time. Because Tully Foote has fully moved to Intrinsic, he can no longer act as the PI at Open Robotics, and therefore we will need to have a new PI assigned at Open Robotics, CEO Vanessa Yamzon Orsi is available for this role.

Although not quite ready for release, the simulator itself is developing nicely and we have completed some initial accuracy tests that compare its performance to the performance of the actual device at sea. The first tests estimate the time-step size required to get converged results from the simulator. This involves running the same case at increasingly small time-steps in order to determine a suitable time-step size. In the interest of reducing computation time, one wants to use the largest time-step possible. Convergence testing indicates that relatively large time-step size of 0.05 seconds provides similar accuracy to smaller timestep sizes, and that the simulation is stable. This is an important result, a timestep size of .01 seconds for instance allows the simulation to run at approximately 10 times real-time speed, compared to at or slightly below real-time speed for a timestep size of 0.001 seconds. This fast execution greatly enhances the usability of the simulator.

After establishing the time-step size required for convergence, the next results provide an estimate of the simulators accuracy by comparing to at-sea performance of the actual device. In these tests the simulator is configured to match the at-sea device, and waves are input that match the sea-state measured during hour-long periods of operation. Figure 1 illustrates some results.

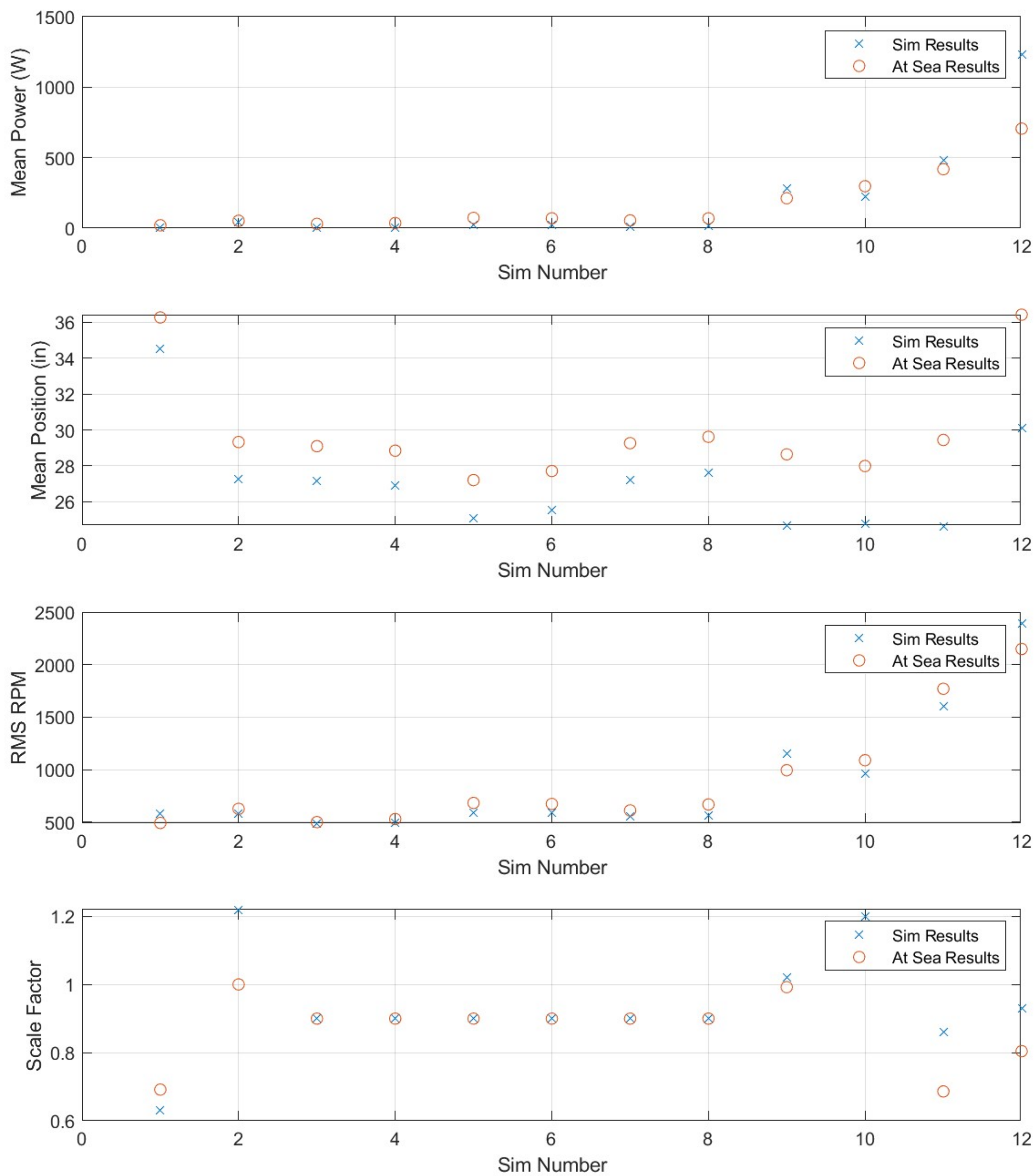

Figure 1: Comparison of Simulated Results with At-Sea Measurements

Because the simulator can only match the wave-spectrum, and not the moment-by-moment wave-heights, comparisons between simulated and actual results must be done in a statistical sense, i.e. comparing the mean or standard deviation measures of quantities. It is not expected that these results will match exactly because there are a number of effects present at sea that are not modelled, such as ocean currents and wind forcing. Nevertheless, these initial results are encouraging and in the future we will be expanding this comparison beyond these twelve hour-long periods to include most if not all of the collected months of at-sea data, and aim for an academic style publication to support and quantify the accuracy of the simulator developed in this project.

Finally, during this reporting period the actual MBARI wave-energy device was prepared for deployment and at the time of this writing the system is at sea and performing well. All of the necessary ROS software is installed on the buoy computer to allow ROS-enabled software to run at sea, and we have a few small applications that support our deployments using this software as proof of concept and use.

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. Once the simulation environment from this project 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. Chris is starting to incorporate this analysis into the comparison to the WEC-Sim simulation.

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. In this reporting period we have made two such presentations. On March 17th of this reporting period, Andrew Hamilton presented this project at the University of Washington/APL Seminar series. As part of that visit Hamilton also met with several graduate students who expressed an interest in the project. On February 22 of this reporting period, Michael Anderson gave a presentation at the online Gazebo Marine Robotics Community meeting, a regular meeting at which developers interested in using the Gazebo platform gather.

e) Plans for the Next Reporting Period

In the next reporting period we expect to make an official release of a complete version of the simulator and simulation environment. This milestone has taken some time to reach but the work is nearly done and we are currently performing final checks and making the software available as a docker image through Dockerhub. As part of this work we are doing some convergence and accuracy testing of the results, and plan to compare results from the simulator to field data taken from the actual buoy. This work requires we run the simulation against the actual sea-conditions that were recorded during previous deployments. We have a collection of data selected for this comparison that overlaps with a similar comparison done by Chris Dizon at Oregon State

University for the purposes of validating the previously developed WecSim model for this device. In the next couple of reporting periods we expect to generate a publication summarizing this work.

Also in the next reporting period we will be deploying the MBARI wave-energy buoy in Monterey Bay. Although this is a routine deployment for MBARI, in this case the system will include all the ROS software developed in this project, and be available to run code developed against the simulator. The original project planning had ambitions to extend this opportunity to outside beta users, however it is likely that this infrastructure will be used immediately by MBARI staff for our investigations by our Sandia National Lab partners.

Finally, PI Hamilton is scheduled to present a seminar for UMERC, the University Marine Energy Research Community. This was previously scheduled for this reporting period but had to be delayed for reasons out of our control.

Products

a) Publications, conference papers, and presentations:

- On March 17th of this reporting period, Andrew Hamilton presented this project at the University of Washington/APL Seminar series.
- On February 22 of this reporting period, Michael Anderson gave a presentation at the online Gazebo Marine Robotics Community meeting, a regular meeting at which developers interested in using the Gazebo platform gather.

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: 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: 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

As discussed above, we are going to require a change in PI on the Open Robotics side of this project, we are preparing this request at the time of this writing.

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 possible users of this project's products. Chris Dizon as a post-doc is beginning to use this projects software for his research work.

- 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 continue to develop a potential user of this software, Johns Hopkins University graduate student Kuzhivila Pannickottu (Nivya). Nivya is a student of Prof. Louis Whitcomb so a potentially good avenue into the robotics academic community.

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 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 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. 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