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

Submission Date

10/30/2022

DUNS Number

178341772

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Project Period of Performance

10/1/2021 - 9/30/2025

Reporting Period End Date

9/30/2022

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	75%	8	
3.4.1	All software packages are published publicly	75%	9	
4.3.1	MBARI control running in ROS system	100%	9	5
5.3.1	Portal ready to launch	60%	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

Work in this reporting period has focused on the simulator development portion of this project, with a small amount of outreach and marketing work. The simulator development work continues utilizing Gazebo, we are working through many details but good progress is happening and we are headed towards having a working version of this system by the end of 2022. This scheduling is a bit behind the original project schedule, but essentially on schedule when the delay in the start of work is taken into consideration. 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

Note that the “buoy_examples” repository listed in previous reports has been eliminated in favor of a simpler structure that has proven effective as we’ve worked with this system. Additionally, we are still considering some name-changes to these working-name versions.

Much of the technical work in this period has been focused on refining the simulation of the specific electro-hydraulic power-takeoff system that is at the heart of the MBARI wave-energy converter. Careful modelling of this device is critical for success in this project because losses throughout that system aren't negligible (as in any real system) and need to be accurately modelled to provide realistic results. To verify the simulators performance, comparisons are being made to the actual device's performance (measured previously in the MBARI labs). Figure 1 illustrates an example comparison for some quantities that result, and provides a sense of the accuracy of the simulator being developed in this project. In these tests a prescribed piston velocity is fed into both the physical device, and the simulator code, and the results are compared as shown. These tests and comparisons are automatically made every time changes are made to the simulation code to ensure simulation fidelity is maintained as the rest of the system develops. Similar comparisons are also made for the pneumatic spring component of the device. Naturally there are some features and noise that exist in the physical device that aren't captured, but there is sufficient fidelity here to provide a useful simulation with a reasonable amount of computational effort. In the simulator we are also including features that report the various loss terms of the system, highlighting where energy is lost in different phases of operation (i.e. friction losses, electrical losses, etc). This capability has been requested in casual conversations with prospective users, and is indeed likely to be useful.

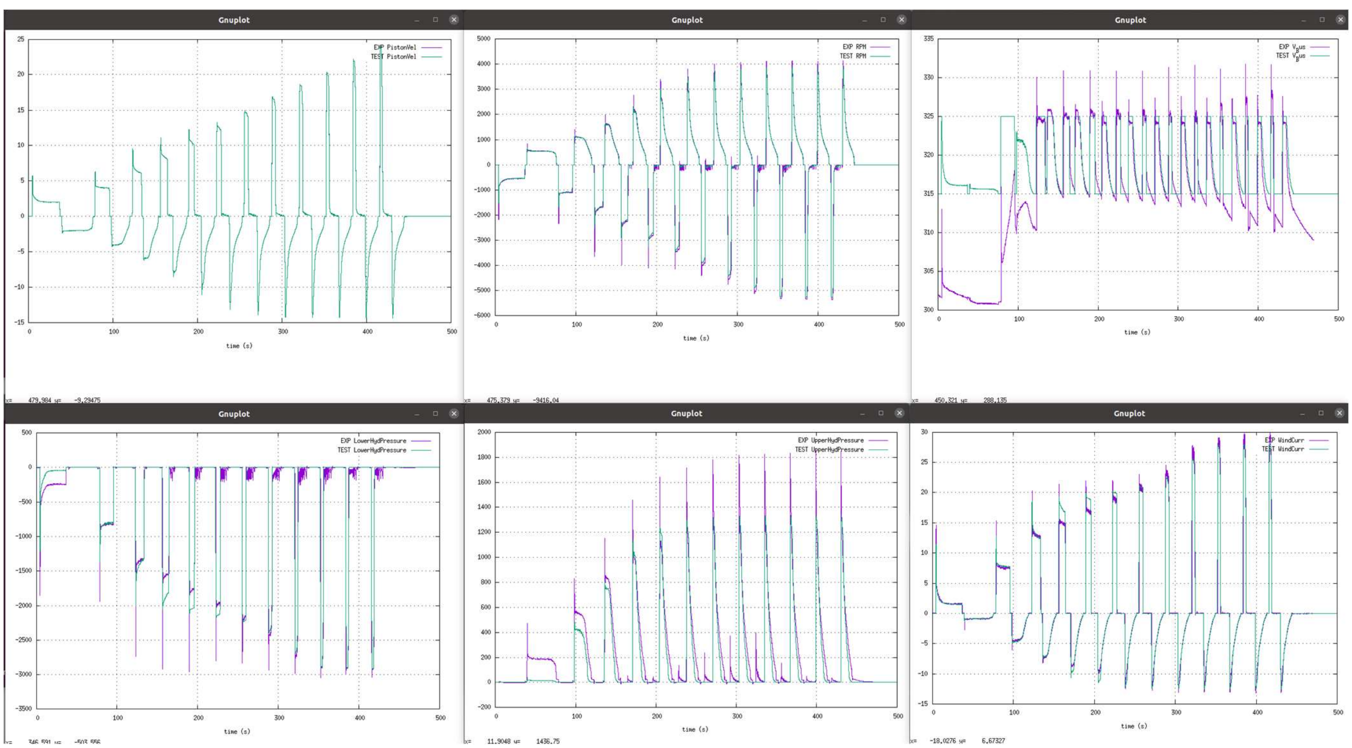

Figure 1: Illustration of comparison between simulated quantities (green), and their analogs measured on the physical device (purple). Input in each case is a prescribed piston velocity, and resulting quantities (motor RPM, Hydraulic Pressures, Electrical voltages and currents, etc.) are compared.

Although there are always improvements that can be made, much of the simulator work is complete, the buoy and heave-cone components are modelled, the electro-hydraulic power take-off device behavior is accurately captured as described above, and the simulated versions of the systems telemetry data and user interface are complete and mimics how the physical buoy behaves.

An outstanding area that we are turning our attention to at this point is the wave-body interaction hydrodynamic behaviors. There are two components of that work, the addition of capabilities to simulate the important added-mass contributions in the Gazebo framework, and the specific code that computes the forces on the buoy due to wave-effects. As previously discussed, the ability to include added-mass effects was not a standard feature in Gazebo, and needed to be added. This work was completed in this reporting period, along with testing to confirm it has been done accurately. The complete feature is now available in the most recent version of Gazebo (code-named Garden) which was released on October 3, 2022. We are currently switching our repositories to use this new version of Gazebo so the added mass terms can be easily included in our simulation.

The wave-forces themselves are also being included in our model, somewhat through the efforts of external collaborator Rhys Mainwaring. As has previously been discussed, Rhys is developing a Gazebo plug-in module that provides the functionality needed by this project, and we are collaborating with him to produce an acceptable result. We are however concerned about becoming dependent on development work being done elsewhere so have adopted an approach in which we are implementing in this project the basic functionality, and simultaneously providing the capability to link with Rhys' expanded work. Further, this projects contribution is being architected in a manner that some of the computations inherent in this type of free-surface wave-interaction hydrodynamic problem are abstracted and usable by Rhys. At the same, time there are other projects pursuing similar goals (Dave Ogden's Chronos work, for instance) and we recently had a meeting with Dave, Rhys, MBARI, and the WEC-Sim team to discuss common goals and approaches. Further progress reports will contain more details of how such collaborations may be best done. In any event, in this project the basic needed functionality has been developed and is undergoing test and verification.

Also in this reporting period, the project has gotten started on providing a framework for documentation of this effort, which needs to ultimately contain a project overview, a user's guide, and tutorials for how to use the result. As outlined previously, we are using the mkdocs platform to generate this documentation and the first results can be seen here: https://osrf.github.io/buoy_entrypoint/. Tutorials are an important component of this user documentation and are under-way, the basic installation instructions are currently on the main buoy_entrypoint readme file but will be adapted to more "step-by-step" instructions and included as part of the documentation site. The next level of tutorial will be step-by-step instructions to get the simulator running so one can see the rendering and data outputs, and control the simulated buoy using the same interface we use control the actual buoy. Then finally, the most complicated tutorials will guide users through creating their own control solutions in this framework. Open Robotics has been contributing some suggestions on what type of tutorials are most effective in this environment, and we are following that result.

An initial outreach and marketing effort was made through a presentation at the ***16th International Conference on Motion and Vibration Control (MoViC 2022****)* in Los Angeles September 7-9. The presentation followed the abstract that was included in an appendix to the last quarterly report. The presentation was well received and a number of established researchers in this field expressed an interest for use by their graduate students, an example of this response is included below. What is clear however is that when presenting this topic, we need to be ready with an operational system for immediate follow-up. In this case it was advertised that we wouldn't be ready until January 2023, but this delay comes at a cost of momentum and interest.

From: "Ossama O Abdelkhalik, AER E" <ossama@iastate.edu>
To: "Andrew Hamilton" <hamilton@mbari.org>
Sent: Friday, September 9, 2022 10:51:43 AM
Subject: MoViC presentation

Hi Andy,

It was great talking to you in the MoViC conference this week. I work in controls of WECs; I currently advise 2 PhD students working on this topic, and have graduated 3 PhDs on the same topic (Shangyan Zou who presented our paper in the conference is one of them). I am very interested in the collaboration opportunities you mentioned in your talk. I am sending this email to start a conversation.

Best regards,
Ossama

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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. We hope to entrain him in doing the same for the Gazebo simulator as that matures.

d) Results Dissemination

The open-source software development in this reporting period represents bulk of the results dissemination as the public at large has had access. As noted above, we also are starting to develop user documentation, currently that documentation is technically also publicly available, but one needs to know where to look. As it matures, we will move it to a more obvious place (perhaps the MBARI web-site) as we advertise its existence. Throughout this past period, we have also become more involved in the maritime robotics community, both through the ROS/Gazebo community, and also through the WEC-Sim group and other National Lab efforts. As described above, we may be able to contribute to a collaborative effort to create a single C++ library for some of the wave-body interaction hydrodynamic computations that are common to several efforts.

e) Plans for the Next Reporting Period

We are aiming to have a complete version of the code and documentation by the end of 2022, corresponding with 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, with Hamilton giving a seminar at Johns Hopkins University on December 6th that will include some details about this project.

Products

a) Publications, conference papers, and presentations:

- On September 7th, 2022, a presentation about this project was made at the *9th IFAC Symposium on Mechatronic Systems (Mechatronics 2022)* and the ***16th International Conference on Motion and Vibration Control (MoViC 2022)***.

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
-

Documentation is available here:

- https://osrf.github.io/buoy_entrypoint/

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 works is now complete. 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, we learned that Louise Poubel at Open Robotics has decided to take a new opportunity, and the management and lead of this effort at Open Robotics has been transferred to Michael Carrol. Michael is equally experienced relative to Louise, and while we were disappointed to lose Louise's contributions, Michael is also a great addition. Also, Joan Mayans was added to the Open Robotics team to tackle the addition of the added mass features, and has made a great contribution there. The names list below reflect these changes.

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: 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.
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. In particular, the simulator development was originally scheduled to be completed in Month 9 of the project, and Month 12 will be more realistic.

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