Introduction

The ongoing DARPA agreement with MBARI (HR0011-09-2-0002) to develop technology for harvesting energy from ocean waves from an autonomous surface platform has the potential to provide an unprecedented renewable energy source in remote areas of the ocean. The proposal described here is for an additional effort to study and test potential approaches for re-charging autonomous underwater vehicles (AUV) from the wave-harvesting platform under development. This is one of the most attractive and transformational potential application for the use of energy generated on-board the wave buoy and has the ability to enable many new observing capabilities in remote parts of the ocean.

Statement of Work

The intention of this add-on effort is to perform three tasks: the first is to perform some concept development and analysis to explore various options for making an appropriate connection between the wave-energy harvesting buoy and typical autonomous under-water vehicles. Similar docking work has been performed at MBARI in the past and it is expected that the experience gained from docking to a stationary, sea-floor mounted, dock will inform the concept development and evaluation.

The second task will be to perform numerical modeling of the AUV and buoy dynamics. The current ocean wave-energy harvesting project has devoted considerable effort to developing a numerical model that predicts the motions of the energy-buoy device in various sea-states. Numerical simulation of AUV motions has been ongoing at MBARI for many years and the ability to run AUV missions in a simulation mode that couples the AUV control system to the vehicle dynamics is well developed. Coupling these two capabilities should be straight-forward and lead to a tool in which mock docking runs can be simulated and statistics of success/failure compiled for different configurations, vehicle types, and sea-states. Additionally, this modeling will allow the controllability requirements for the AUV to be determined for each docking concept under investigation.

The final task will be to perform a proof-of-concept experiment that will address a high-risk aspect of the docking problem. Possibilities include homing and navigation issues related to near-surface operation, mechanical mating and capture of an AUV to a moving surface platform, and electrical/data connection between the surface buoy and AUV. The exact nature of this experiment will be dictated by the first two project tasks, it will however likely include one or more at-sea tests of an AUV operating in close proximity to the energy harvesting buoy or similar mock-up.

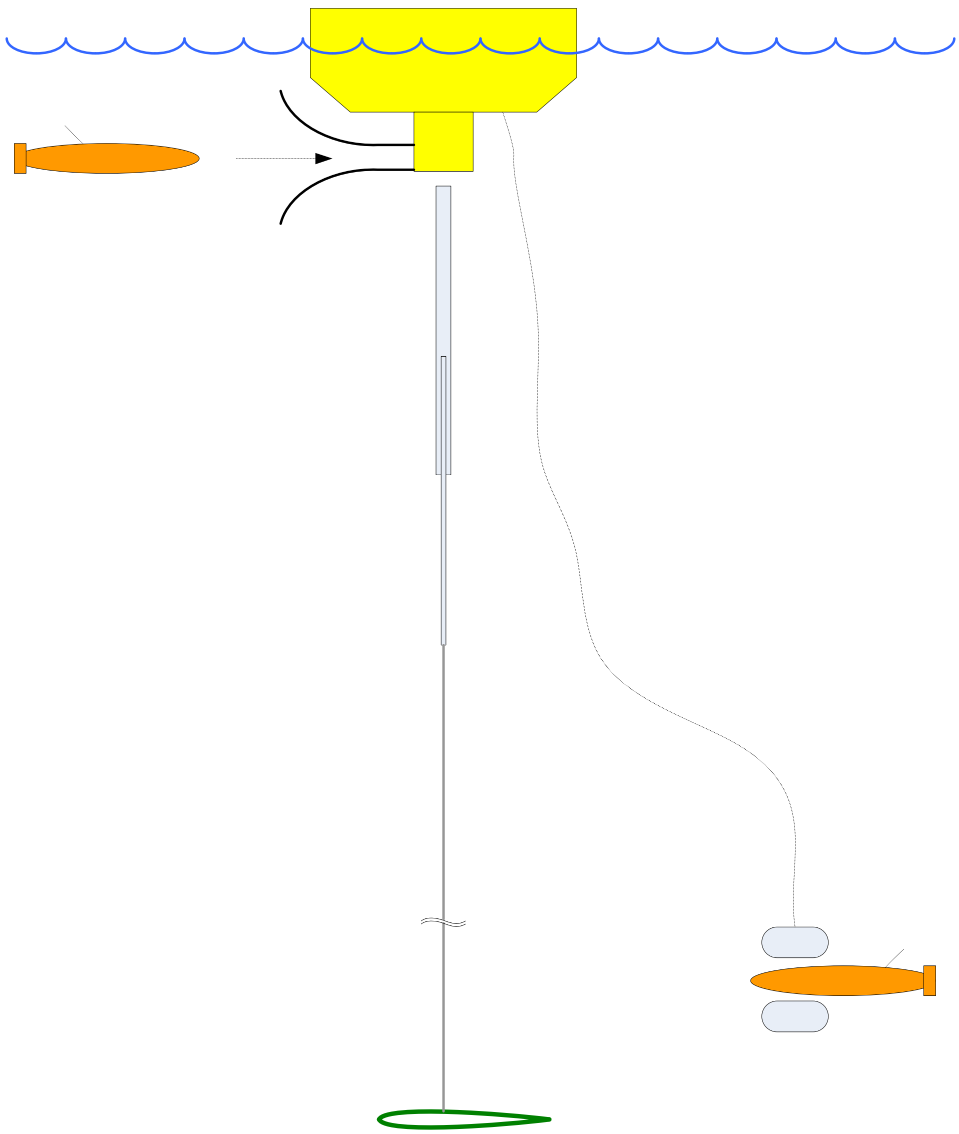

Figure 1: Concept variations for AUV docking to wave-energy buoy.

Technical Approach

The concept development component of the effort will include an analysis of the various options available for docking an AUV. There are a number of design possibilities, two of which are illustrated in Figure 1. The upper AUV dock shown borrows from the “cone dock” concept that was successfully implemented at MBARI for the case in which the dock itself was a fixed platform on the seafloor. In that case the dock cone was six feet in diameter for a vehicle that was 21 inches in diameter and 14 feet long. Repeated docking was achieved and it was found that the AUV could be placed reliably within a three foot diameter circle centered on the dock cone. That system used a sonar beacon located on the dock and an ultra-short-baseline (USBL) sonar receiver in the nose of the vehicle. That sonar system provided the vehicle a continuous range and bearing to the dock, which was always located in the same place and oriented in the same direction. After the vehicle entered the dock a pin was extended from the dock to secure the vehicle in the tube, power recharging was performed inductively and communications were performed using a RF link (a modified wi-fi system) that is useful for ranges of one-two centimeters underwater. A video of the MBARI AUV successful docking is located at: http://www.mbari.org/staff/rob/three_docks/three_docks.html

Although this is a proven docking solution, there are several challenges in adapting this cone dock system to be used below a freely floating buoy. The first concern is the ability of the vehicle to maneuver sufficiently to insert itself into the dock in the presence of surface waves. This task is complicated by the fact that the dock's location and orientation is not fixed and thus this information must be transmitted to the vehicle during the docking procedure. Because the USBL system is able to provide buoy location information to ranges of several hundred meters, it will be sufficient for the vehicle to surface nearby and get a buoy position fix over a terrestrial or satellite radio link and rely on the USBL for short range homing. The buoy's direction information is more complicated, if the buoy rotations tend to be slow, the buoy's orientation at the time of the position fix may be sufficient; otherwise buoy direction signal will need to be transmitted to the vehicle by another manner (acoustically or possibly via an electro-magnetic modem system that is under test at MBARI right now) during the final homing maneuver.

The main unknown question about this cone-dock approach is the vehicle's ability to maneuver sufficiently to hit a dock that is moving in the waves. Additionally there are concerns about the safety of the vehicle underneath the heavy buoy in large sea-states and the effect of a large cone structure on the station-keeping performance of the buoy. There isn't an obvious way to store the cone dock out of the way when not in use.

The second concept illustrated in Figure 1 includes a remote dock that is not rigidly connected to the wave-energy buoy but is instead lowered to an appropriate depth when docking is to be performed. The idea here is that a catenary shape in the tether connecting the two bodies will decouple the dock motions from the buoy motions. This "mid-air refueling" docking concept has not been implemented but would again likely rely on a USBL system for homing. There are challenges with this concept as well, including the possibility of tangling the docking tether with the submerged mass tether, although it would be equally possible to have the dock descend from the submerged mass device itself, eliminating this problem.

The two concepts illustrated in Figure 1 are just representative and the first task of the effort will explore the possibilities of these concepts and others that come to light as various homing and docking strategies are considered.

Numerical Modeling

The evaluation of any docking concept presents a number of questions, some of which can be appropriately evaluated by numerical modeling of the dynamics of the system. In particular primary questions include:

- For a vehicle of particular maneuverability characteristics, can successful docking be achieved in various sea-states?
- Is there a preferential direction that the vehicle should approach the dock relative to the wave field?
- How accurate do the vehicle's sensors (such as depth) need to be to navigate in the near-surface environment?

- Does the vehicle need to get updated dock orientation information during a docking maneuver or is the USBL data sufficient?
- Does the tether connecting the submerged dock adequately de-couple the docks motion from the buoy motion?

The on-going wave-energy effort has included the development of a fairly sophisticated numerical modeling tool that predicts the motion of all elements of the wave-buoy device in response to a specified wave and wind state. This model solves the equations of motion of the buoy system in six degrees of freedom based upon a specified wave-field input and has been validated by experimental results. Over the past 10 years at MBARI, considerable work has also been done in modeling the dynamics of AUV's and simulation tools exist to predict the motion of particular AUV's in response to commanded motions (turning, depth change, etc) and external disturbances. These tools exist in two forms, the first is a Matlab based solution of the vehicle's equations of motions, this is useful for examining the vehicles expected controllability characteristics in different configurations. The second form includes the actual vehicles flight-code and allows simulations to be performed of particular missions in a manner that exercises the exact code that will be running when the vehicle is deployed at sea. Together these tools have been invaluable in understanding vehicle dynamics and avoiding costly errors at sea in mission configuration and execution.

To examine the questions outlined above relative to the near-surface docking problem a combination of the two models will be required. Output of the wave-buoy numerical model provides a six degree-of-freedom prediction of the buoy-system motions (floating and submerged elements) in response to a specified sea state. Also available is the water velocity vector as a function of location relative to the buoy for all times of the simulation. These outputs will then be used as inputs into the vehicle dynamics simulation code, allowing the vehicles behaviors to be modeled in the environment immediately surrounding the wave-buoy device. Although it would be possible to solve the vehicle dynamics equations of motions simultaneously with the buoy motions, this is most likely not necessary because it is safe to assume that the vehicle motions do not affect the buoy motions or surrounding wave field.

With these two models combined in this way, realistic modeling of various docking approaches can be performed. The vehicle dynamics will be solved, complete with the appropriate vehicle control loops which will take a docking behavior algorithm as input along with simulated behavior of the USBL homing system or other sensors such as depth sensors. With this approach, questions about the vehicle controllability and sensor requirements can be investigated to determine if docking in this manner is possible with current vehicles and sensor suites. Additionally, by introducing a stochastic element to these simulated signals, a monte-carlo analysis can be performed and docking success statistics generated in various sea-states.

These techniques apply equally to the two docking concepts described above, as well as other potential approaches. In the case of the "mid-air refueling" approach, the dynamics of the tether connecting the two bodies will play a significant role in the behavior of the system and will need to be modeled accurately. This modeling is beyond the current capability and either will need to be added to the code or incorporated through the use of commercially available tools such as OrcaFlex. Time has been included for outside services to perform this aspect of the modeling.

Field Testing

Although significant insight can be gained from the numerical modeling techniques described above, those results need to be validated by some at-sea tests. Additionally, there are a number of questions about the feasibility of the docking concepts that can only be accurately assessed through testing:

- Do current USBL systems behave reliably near the ocean surface? There is certainly the possibility that noise and reflections due to the sea-surface will reduce the effectiveness of this sensor.
- Does the buoy platform rotate quickly enough to require that an orientation update is provided to the vehicle in real time during the docking maneuver?
- Does a tether between the wave-buoy device and a remote dock sufficiently de-couple the dock motions from the buoy motions? Although in principle this can be modeled by solving the cable-dynamics equations of motion, the phenomenon involved are highly non-linear and any such results would need to be validated by an at sea test.

Although the exact nature of the field component of this proposal will be dictated by the results of the numerical modeling, it is expected that this stage of the project will involve one or more at-sea tests of an AUV operating in the vicinity of the wave-energy buoy or suitable mock-up. It is possible that this test will include an actual docking device, or perhaps just enough instrumentation to demonstrate a sufficient homing behavior to enable docking. The infrastructure to actually perform the mechanical and electrical connection to a vehicle is non-trivial and since these aspects have been demonstrated previously in other docking efforts (at MBARI and elsewhere) these elements will most likely not be part of this effort. At the mid-project review meeting shown in the schedule below, the exact field-test plans will be presented.

There are three levels of complexity possible for the field testing component of the project:

- The simplest useful test would not include an at-sea measurement of motions and behaviors of the docking elements connected to the wave-energy buoy solution and would not include an AUV. By instrumenting the dock with appropriate sensors, it's orientation and motions would be measured to validate the numerical modeling and provide information about the docking environment an AUV would need to adapt to.
- A more complex test would include an appropriate homing system in addition to the above instrumentation. This test would include an AUV operating in the vicinity of the dock, making measurements of the homing system behavior and performing homing exercises that approach, but do not mate with the dock.
- The most complex test would include the above and would also include a mechanical capture of the AUV in a way that would demonstrate docking to the wave-energy buoy.

The most complex test described is beyond the scope of this proposal and the field test has been scoped to allow a test somewhere between option one and two. It is expected that existing AUV resources at MBARI would be used in the case that the test includes AUV operation.

Cost, Schedule, and Milestones

A high-level schedule for the project tasks is shown in Figure 2, Task 1 and Task 2 overlap in time because there will be some iteration necessary between the efforts.

These first two tasks are scheduled to end at the same time as stage 2 of the wave-energy project. The field test in task three is scheduled to overlap with stage 3 of the wave-energy project, which is also a field demonstration effort.

The three components outlined in the statement of work have costs associated with them as follows:

Task 1: Concept Development and Trade Study Analysis

- Duration = 4 months, overlap with task 2 (ID #1 in figure 2).
- Total Cost = $39,325. Burdened cost of 1.5 engineering months for appropriate MBARI personnel.

Task 2: Numerical Modeling

- Duration = 4 months, overlap with task 1 (ID #2 and #3 in figure 2).
- Cost = $293,108. Burdened cost of 12 engineering months for appropriate MBARI personnel, 2 domestic trips for technology exploration, 120 hours of outside services for tether dynamics modeling as needed.
- Milestone = Project Review meeting (5/1/2011).

Task 3: Field Experiment

- Duration 11 months (ID #4, #5, and #6 in figure 2).
- Cost = $627,206. Burdened cost of 24 engineering/technician months for appropriate MBARI personnel, 60 Hours of outside services for fabrication, 7 days of Zephyr ship time for testing.
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Equipment and Material Breakdown (estimates)	
Materials (steel, aluminum, plastics)	$10,000
Motion sensing detectors (AHRS)	$10,000
Fasteners, fittings, cabling, slip-rings	$10,000
Homing components	$20,000
Underwater video cameras	$10,000
Totals	**$60,000**

- Milestone = Final project report. (3/25/2012).

Total Duration: 18 months
Total Cost: $959,639

ID	Task Name	Start	Finish
1	Concept Development and Analysis	11/1/2010	3/2/2011
2	Numerical Modelling	1/3/2011	4/29/2011
3	Review Meeting	4/29/2011	4/29/2011
4	Field Experiment Preparation	4/29/2011	11/25/2011
5	Field Experiment Activities	11/1/2011	3/1/2012
6	Prepare Final Report	3/1/2012	3/26/2014

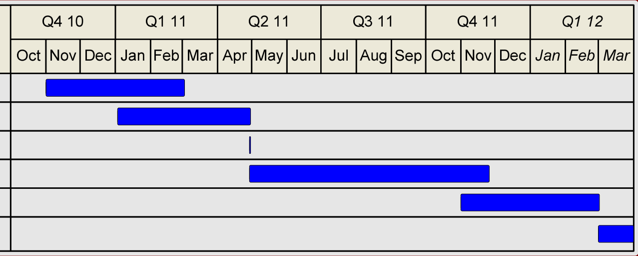

Figure 2: High level schedule for AUV docking effort.