Introduction

The ongoing Renewable At-Sea Power (RASP) program has developed test hardware that captures modest amounts of energy from the ocean waves and converts it to electricity. This system consists of a floating surface buoy and a submerged flat plate that are connected together by a power take-off device. This electro-hydraulic device converts the mechanical energy present in the relative motion of the buoy and submerged plate to electrical energy that can be stored in buoy based batteries. Figure 1 illustrates the arrangement of the system.

Numerical modeling and test deployments to date indicate that this hardware is capable of capturing and converting about 300W of power on average in sea states typical of Monterey Bay California. Although numerical modeling was performed to optimize the size/power tradeoff of the elements of this system, the control strategy of the energy conversion equipment has been implemented as a simple linear damping effect that is sub-optimal. Recent research related to utility scale wave-energy conversion systems indicates that by implementing control schemes that adjust the resistance of the power take-off system on a wave-by-wave basis, a doubling or tripling of the wave-energy captured by the device can be achieved. This proposal outlines additional work to develop, implement, and test such control schemes.

In general the project is well poised to tackle this work, the specific numerical modeling tools developed so far have been verified and calibrated against many hours of at-sea tests and are directly applicable to analyzing the optimal control problem through computer modeling. The hardware developed has all the needed computing, power-electronics, and sensor infrastructure needed to implement the resulting control algorithms in full-scale at-sea tests. And finally, the lab-test environment developed for this project is capable of testing the power take-off system at full speed and load, increasing the likelihood of successful sea tests.

Goals and Deliverables

The goal of this effort is to enhance the control system of the wave-energy conversion device to increase the amount of energy captured in a given sea state. Preliminary estimates indicate that a doubling or tripling of captured energy relative to the simple control scheme currently utilized is possible. Table 1 shows the goals for three sea-state ranges. The more aggressive goal for the low sea-state is because currently the system efficiency relative to the theoretical maximum power capture is the lowest in this region and the tendency for the system to “cut-out” in waves below 1m is a significant limitation to high average power numbers. Similarly, the project will not spend significant amounts of time optimizing the system in large sea-states since even at low efficiencies high power levels result and as the wave gets bigger other considerations (survivability) tend to dominate the control scheme algorithm.

The work performed in this project will lead to two main results which will be presented in a final report and possibly other technical publications. The first will be the results of a numerical study of the system dynamics and various candidate control schemes. The second will be an analysis of data collected from the at-sea testing.

Sea State	Significant Wave Height	Mean Power Increase Goal	Mean Efficiency Increase
Low	0.5-2 meters	3 X	6% -> 18%
Medium	2 - 4 meters	2 X	12% -> 24%
High	> 4 meters		

Table 1: Goals for the power capture increase that will result from this project in three sea-state ranges.

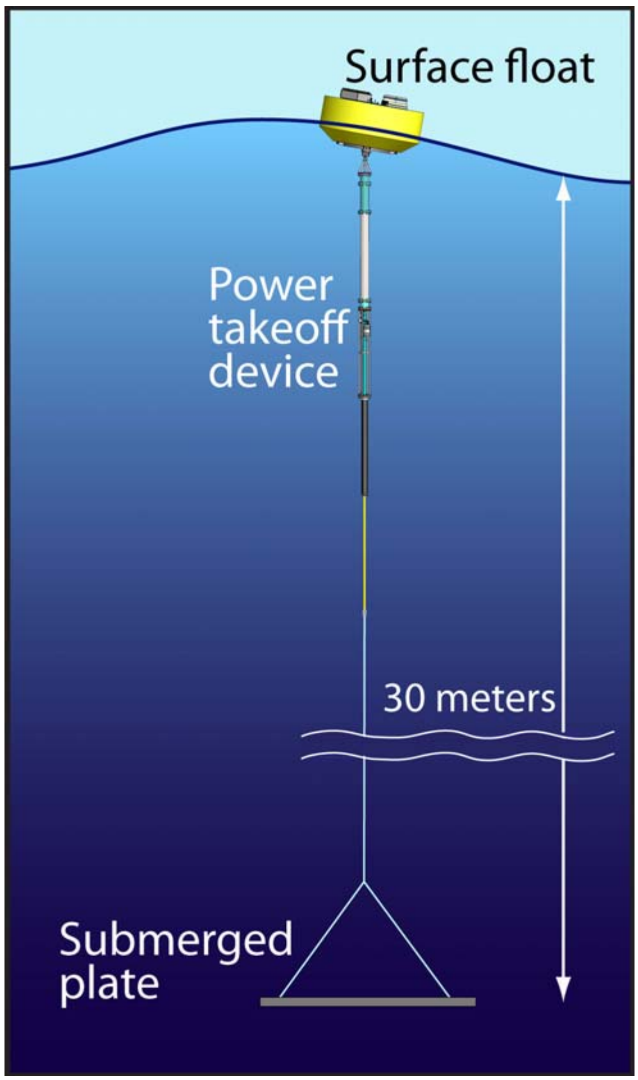


Figure 1: Illustration of the wave-energy conversion device developed as part of the ongoing project.

Statement of Work

The proposed effort consists of three tasks:

1) Use the existing numerical modeling tools to develop and analyze control schemes that will maximize the energy captured by the wave-energy conversion device. As noted above these tools do not require modification to do this so the bulk of this effort will be spent developing and numerically testing relevant control schemes. Existing strategies from the literature will serve as a starting point and these will be analyzed and modified as needed. The result of this task will be a comparison of the utility of existing control schemes to this specific wave energy conversion device topology, and one or more candidate control schemes that can be implemented and tested.
2) Implement one or more control schemes into the existing hardware. It is expected that this will be largely an embedded software effort to modify the existing system to adjust the systems response to a variety of sensors that exist in the system (force, motion, etc). Depending on the algorithm, it is possible that one or more additional sensors will be needed. The existing hardware has expandability to accept these sensor inputs with relatively little modification.
3) At sea tests and data analysis. Two deployments of about a month each are proposed. The extended time-frame allows data to be collected in a variety of sea states and reduces the risk of abnormal sea conditions that can occur during shorter deployments. The two deployments will be separated by a number of months to allow for data analysis and algorithm improvements between tests.

Technical Approach

A “point-absorber” type wave energy conversion device such as the one developed here moves on the water surface in response to incoming waves, and generates outgoing waves as a result of this motion. The amount of energy absorbed by the device (which can then be converted to electricity) is exactly equal to the destructive interference that occurs between the incoming and outgoing waves. The goal of an optimal control system is to apply a load to the power take-off system that encourages the buoy motions to generate an outgoing wave that most destructively interferes with the incoming waves. Because the incoming waves are two-dimensional, and the outgoing waves are circular waves, perfect destructive interference is impossible and there is a maximum amount of energy that can be captured. This maximum absorbable power is proportional to the product of the volume of the device, the incoming wave height, and the incoming wave frequency. Figure 1 illustrates these maximum theoretical limits as a function of incoming wave period and shows schematically how two different control schemes may behave.

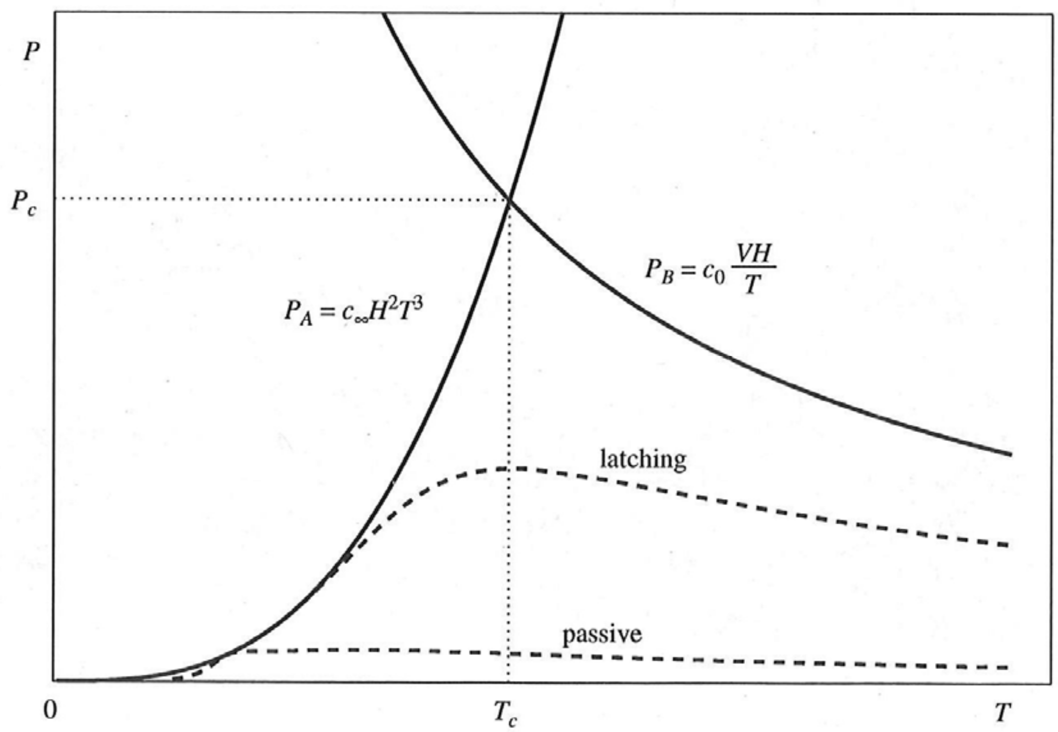


Figure 2: Illustration of relative levels of power absorbed versus that which is theoretically possible for a given wave height (H) and device volume (V). Representative lines for a passive and latching control scheme are shown. Reproduced from Hals [2011] without permission.

The simplest possible power take-off control scheme has been implemented to date; this consists of exerting a force that is proportional to the velocity of the power take-off ram speed. This passive "resistive loading" approach is sub-optimal because the phase of the incoming and outgoing waves are rarely far apart and relatively little destructive interference occurs. Additionally, each sea state requires a different value of damping and if one value is set, the system will rarely be tuned correctly as the sea state changes from day to day. A better performing system can be created by occasionally "latching" the power take-off ram for a portion of each wave period. If done correctly this causes the buoy to oscillate more out of phase with the incoming waves and the total energy capture increases. These two options are shown as dotted lines in Figure 2. The next level of complexity involves the "reactive" flow of power back into the system at portions of the wave cycle in order to even better position the phase of the buoy motion relative to the incoming waves. Although this is the most optimal option, the complications that result in the power electronics are significant and such a system is much easier to realize in simulation than in practice. Figure 3 illustrates specific numerical results for a range of strategies applied to a larger system that produces power in the range of 10's of kilowatts. As shown, the non-reactive schemes (PML and PMC) demonstrate a significant improvement in power conversion over the resistive loading (RL) scheme currently implemented.

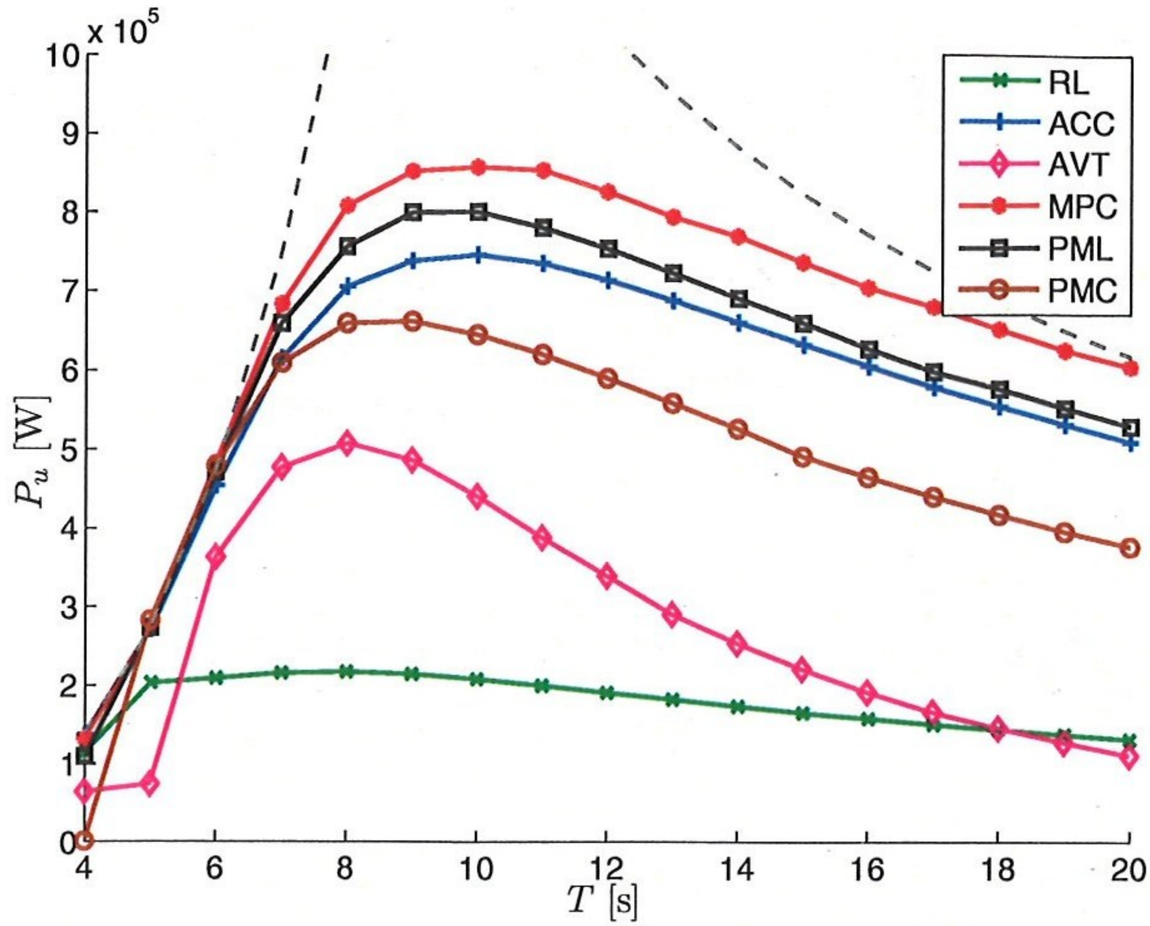


Figure 3: Average absorbed wave power for different control strategies. “RL” is a simple linear damper model for the power takeoff. “ACC”, “AVT”, and “MPC” are reactive schemes, the rest are non-reactive. Reproduced from Hals [2011] without permission.

Although extensively studied, the results in the literature cannot be applied directly without further refinement. This is because the systems typically studied have a simpler topology than the wave energy converter developed in this project, and because mostly larger utility scale machinery has been analyzed. The existence of the submerged plate in this projects design creates a two-body system whereas most previous optimization work is oriented toward a floating body tethered directly to the seafloor via power take-off machinery. There has been work showing a mathematical equivalency between the two-body and single-body floating systems and therefore similar results to Figure 3 are expected, but the implications on the optimization techniques are not clear and will be a significant result of this work.

An additional difference between the proposed work and existing work is that very little of the studies in the literature include efficiency characteristics of the power take-off device. Although understandable for this type of study, this has the potential to produce misleading results. For instance, a control scheme that drives the power take-off system to speed/force regions that aren’t efficient may look better than can be realized. Because this project has done extensive efficiency testing of the power take-off system in the lab, these characteristics can be included in the control scheme evaluation proposed.

To determine the best scheme that can be implemented, it is proposed that numerical modeling of the system and control scheme is performed prior to implementation and at-sea tests. Only non-reactive schemes will be investigated since the existing hardware does not support driving the power take-off element in reverse.

Numerical Modeling

The numerical modeling tool developed as part of this project is a non-linear time-domain simulation that takes as inputs the characteristics and topology of the system, the incoming wave field, and the control scheme. Outputs include predicted motions, forces, and power levels for the system in that sea state. Numerical studies have been done to optimize the system size based on the simpler “resistive loading” scheme described above and it is proposed that this tool be extended to analyze more sophisticated control schemes.

The tool is well suited to this task with little modification so the bulk of the effort will be concentrated on designing and comparing control algorithms. Because it is a numerical simulation, all current states of the system are perfectly known during the simulation. Careful thought will need to be given to what information is measurable on the system and how observable and noise-free the data is. Additional filtering will be added to the simulation to realistically mimic the quality of the data that can be used during implementation. For measurements that are already being made in the system (motions, forces, etc), this filtering will be performed through comparison to measured results from previous deployments. For any new measurements that may need to be added, estimates of noise on those channels will be included.

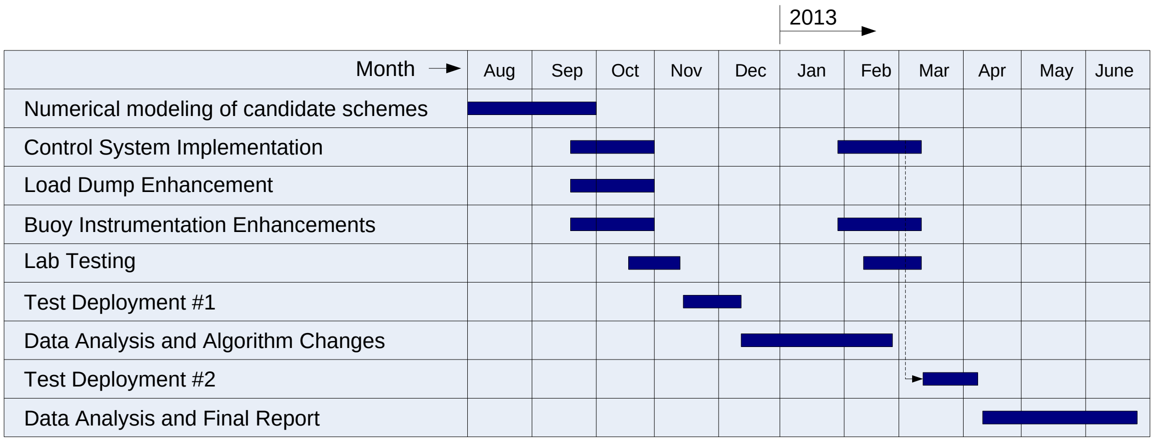
Because the system has nonlinear elements (drag forces and the behavior of the power take-off system), it is expected that the optimization will require many scenarios to be modeled. The numerical model runs quickly enough that dozens or hundreds of simulations can be run in a day, allowing established constrained optimization techniques to be employed to locate the areas of the design space that show the most promise.

Implementation and Field Testing

It is expected that the existing deployable hardware can be used for this project nearly unchanged aside from software. There is a possibility that additional measurements such as buoy draft may need to be made to achieve the best result. The computing infrastructure in the system has the capacity to have 6-10 additional sensors added if needed and this is highly likely to be sufficient for these purposes. Two deployments of roughly one month duration are proposed. This will allow an iterative approach to the algorithm design and will additionally provide more time at-sea for the device to address the longevity questions of the system.

Cost, Schedule, and Milestones

The schedule is organized around two one month long test deployments, one in November, 2012 and the other in March 2013. These deployment dates are chosen to avoid the winter conditions and the typically calm conditions in early October.



Optimal Control Activities

Activity	Labor (hours)	Material Cost	Ship Costs	Total Cost (burdened)
Numerical Modeling of Candidate Schemes	420			
Control System Implementation	320			
Load Dump Enhancement	150	$5,000		
Buoy Instrumentation Enhancements	160	$10,000		
Lab Testing	240	$5,000		
Test Deployment #1	120		$6,825	
Data Analysis and Algorithm Changes	240			
Test Deployment #2	120		$6,825	
Data Analysis and Final Report	360			
Total	2130			

Budget Justification

Ship Time

These deployments will use the same ship and procedures as previous deployments of this system. The cost estimates are based on the daily rate of the boat and our experience that it typically takes 2 days for deployment and 1.5 days for recovery.

Labor

The labor estimates include the same personnel that have been used to date on this project. The hourly estimates are best estimates based on the scope of work.

Materials

Because this add-on proposal uses equipment developed as part of the larger effort, there are no large purchases required. The costs included are to the following items:

- Consumable items related to the deployments (oil, cables/ropes, etc),

- Additional instrumentation needed to implement control schemes (i.e. pressure sensor to determine the buoy draft in real time).
- Power electronic components needed to increase the capability of the load dump system to handle higher peak powers.
- Materials for lab testing of new elements.

References

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