CONNECTING TO THE OCEAN'S POWER

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MARINE ENERGY RESEARCH AT APL-UW

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MARINE ENERGY RESEARCH AT APL-UW

Opportunities & challenges

The ocean contains vast amounts of energy that could be harnessed to meet electrical power needs for applications including, but not limited to, autonomous ocean observation, expeditionary power, and national electric grids. APL-UW is focused on advancing the Navy's capability to utilize two of these ocean resources: currents and waves.

Relatively strong currents (> 1 m/s) are produced by the exchange of water through narrow channels with the rise and fall of the tides and by wind-driven circulation in ocean basins (e.g., western boundary currents, such as the Gulf Stream). Regardless of the source of these currents, they can be harnessed by turbines that are similar in appearance to those used to harness wind energy. To generate power from intense and predictable currents, these turbines must overcome a number of unique challenges, including reliability, resistance to corrosion and biofouling, and multi-objective control.

The ubiquitous nature of ocean waves makes this a strategically important marine energy resource to harness for the U.S. Navy. While waves are also produced by wind, they have fundamentally different characteristics – in addition to the visible crests and troughs, they produce strong oscillatory motion and pressure fluctuations beneath the surface. Because there are no terrestrial analogues to wave energy, the pace of technology development and utilization has been slower and significant innovation is required to deploy cost-effective wave generation systems, particularly those that can operate without a surface expression.

Shared across waves and currents are system integration considerations related to the sizing and operation of hybrid ocean microgrids and design of efficient power electronics for autonomous sensing and vehicle recharge. Taken together, utilization of marine energy at any scale represents a grand challenge – one that APL-UW is well-positioned to overcome.

R & D at a university lab

The Applied Physics Laboratory of the University of Washington is a world-renowned center for scientific and engineering research and development. APL-UW's research portfolio addresses the basic science priorities of national, state, and private agencies and the applied priorities of industry and Department of Defense agencies. APL-UW was founded eight decades ago and has maintained a strong strategic partnership with the U.S. Navy as a University Affiliated Research Center.

To meet the evolving needs of federal research sponsors and the U.S. Navy, APL-UW has core expertise in ocean physics, engineering, medical and ocean acoustics, polar science, environmental remote sensing, and signal processing. Now, capabilities in marine energy technology have been added as a core area of expertise. The U.S. Navy's support to the University of Washington, one of the nation's preeminent research universities, leverages APL-UW capabilities with university academic expertise to address a wide range of topics in marine energy through experimentation and evaluation in laboratory settings and field deployments of prototype systems.

Next generation

Sustained NAVFAC support has helped establish APL-UW and its partners as national leaders in marine energy research. Project funding has built a deep pool of science and engineering expertise in the field and provided hands-on research experience for students pursuing academic degrees in fields relevant to marine energy. Many of these professionals and students, whether continuing careers in academia or moving to industry or national laboratories, remain engaged in marine energy research and development.

Task descriptions

APL-UW and its partners at the University of Washington and Oregon State University have performed Navy-sponsored applied research related to renewable energy since 2015, building on a foundation established by other federal agencies. Completed and ongoing projects reflect a broad range of scopes and outcomes. Some have supported the development of critical marine energy infrastructure (N00024-10-D-6318/0037) while others have supported single project field deployments (N00024-08-D-6323 to 0016[2], N00024-10-D-6318/N00024-20-F-8708). Other supported applied research activities include numerical modeling, laboratory experiments, and field studies associated with marine energy resource assessment, conversion, energy storage, and related technologies.

TASK ORDER TITLE	TITLE
N00024-10-D-6318/0037	MHK Advancement for Naval Facilities ($7,996,918; 4 yrs. 3 mo.)
N00024-10-D-6318/0067	MHK Array and Component Optimization & Testing ($2,417,625; 3 yrs.)
N00024-10-D-6318/0072	Marine Energy Converter Field Demonstrations for Naval Facilities ($2,286,599; 4 yrs. 1 mo.)
N00024-10-D-6318/N00024-18-F-8702	Optimization of Marine Hydrokinetic Energy Systems for Naval Applications at Multiple Scales ($6,000,000; 5 yrs.)
N00024-10-D-6318/N00024-20-F-8708	NAVSEA Task Turbine-Lander ($1,400,000; 3 yrs.) [1]
N00024-21-D-6400/N00024-21-F-8712	NAVSEA Task Marine Energy Development for Naval Applications ($6,750,000; 4 yrs.) [1]
N00024-21-D-6400/N00024-22-F-8719	Marine Energy R&D 2 ($2,862,391; 3 yrs.) [1]
N00024-08-D-6323 to 0016[2]	WETS Integration and Deployment of Adaptable Monitoring Package ($750,000; 19 mo.)

[1] Work on these contracts is ongoing
[2] Subcontract from University of Hawai'i Applied Research Laboratory

Marine energy research team

To achieve broad research goals and meet NAVFAC needs, APL-UW's marine energy program is driven by a group of leaders with diverse research and development portfolios, and relies on professional staff engineers as well as undergraduate and graduate students. APL-UW investigators coordinate with campus departments that are active in the marine energy space and are affiliated with the Pacific Marine Energy Center. As a result, marine energy researchers at APL-UW can tackle a wide range of applied research and engineering challenges relevant to the generation of power at sea.

APL-UW program leadership

Christopher Bassett, APL-UW Senior Mechanical Engineer, PMEC Associate Director, primary contact for NAVFAC programs at APL-UW and an Affiliate Assistant Professor of Mechanical Engineering UW. *Primary areas of focus:* environmental impacts of marine energy, passive/active acoustics, coordination of field-scale testing.

Brian Polagye, Professor of Mechanical Engineering UW, APL-UW Adjunct Investigator. *Primary areas of focus:* marine energy technology development and optimization through laboratory-scale experiments, instrumentation to understand acoustic effects of marine energy.

Jim Thomson, APL-UW Senior Principal Oceanographer, Professor of Civil and Environmental Engineering UW. *Primary areas of focus:* ocean surface waves, turbulence, physical oceanography, wave energy conversion, resource assessment for waves and currents.

Geoffrey Cram, APL-UW Principal Mechanical Engineer. *Primary areas of focus:* hydroacoustic systems; hydrokinetic energy systems, including storage; advanced seafloor geodetic instrumentation. Licensed Professional Engineer in Washington State.

SCIENTISTS & ENGINEERS

Justin Burnett
Gemma Calandra
Corey Crisp
Ben Cunningham
Alex De Klerk
Morteza Derakthi
Jesse Dosher
John Duong
Emily Iseley
James Joslin
Dana Manalang
Aaron Marburg
Derek Martin
Anuscheh Nawaz
Jess Noe
Joe Talbert
Greg Talpey
Owen Williams
Harlin Wood
Kevin Zach

POSTDOCTORAL RESEARCHERS

Trevor Harrison*
Curtis Rusch*
Kate Van Ness
Kristen Zeiden

*Rusch and Harrison have made noteworthy contributions to marine energy research at APL-UW and have assumed leadership roles in ongoing projects.

STUDENTS

Ari Athair
Trent Dillon
Brittany Lydon
Sarah Palmer
Abigale Snortland

FORMER LEADERSHIP

Andy Stewart, APL-UW Principal Engineer, primary contact for NAVFAC programs at APL-UW. *Primary areas of focus:* marine energy technology development, underwater robotics, haptics, naval architecture.

Tim McGinnis, APL-UW Senior Principal Engineer, Ocean Engineering Department Head. He led many marine energy projects as Principal Investigator before his retirement.

FORMER SCIENTISTS & ENGINEERS

Cassie Riel, Paul Gibbs*, Paul Murphy

*technical lead for Turbine-Lander

FORMER STUDENTS & POSTDOCTORAL RESEARCHERS

Hannah Aaronson
Ramona Barber
John Bates
Justine Brakefield
Robert Cavagnaro
Pranav Chandran
Dominic Forbush
Maricarmen Guerra-Paris
Ama Hartman
Teymour Javaherchi
Madeline Riddle
Hannah Ross
Daniel Sale
Isabel Scherl
Carl Stringer
Ben Strom
Ben Terry
Zack Tully
Andrew Winter

R/V RUSSELL DAVIS LIGHT

R/V *Russell Davis Light* joined the APL-UW research vessel fleet in 2018. Driven by the need to test field-scale marine energy technologies, several unique features were included in its design, making it a one-of-a-kind, multi-use research platform. The vessel's construction was funded by the U.S. Navy, Washington Department of Commerce Clean Energy Fund, and the University of Washington. Since entering service, it has been used to perform research for the U.S. Navy and U.S. Department of Energy.

A gantry rising over the open water between the catamaran hulls at the bow enables marine energy converter testing. Various gantry-supported frame geometries and associated electrical components allow for the mounting and testing of tidal turbine systems without the complication of seabed infrastructure. Tidal turbine testing is performed by lowering frame-mounted rotors to depths below R/V *Light's* hulls, at which point the vessel's propulsion system turns any body of still water into an enormous 'test tank'. A 20' air-conditioned container positioned aft of the gantry system provides a comfortable space for project staff to monitor critical systems and store specialized equipment for marine energy research.

Test & evaluation of marine energy systems

R/V *Light* has been used to develop and characterize cross-flow and axial-flow turbines using three different power take-off (PTO) systems. These tests have included the Turbine-Lander system with a four-blade rotor and related tests studying the benefits of dual turbine control strategies using two Turbine-Lander PTO units configured with two rotor blades. In early 2023 the first test of an axial flow turbine was performed. The vessel has also been used to stress test end-to-end systems prior to deployments on the seabed and by undergraduate engineering students for capstone research. In 2022 R/V *Light* was moored in Agate Pass, WA to support the first Turbine-Lander system deployment in salt water.

In 2021 Aegis Marine Energy used R/V *Light* with APL-UW support to characterize their high-solidity current turbine. This capability is available to industry and academic users as a Teamer facility (teamer_us.org). APL-UW welcomes future collaborations that utilize the vessel's unique capabilities.

Kevin Williams (Executive Director), Brian Polagye (PI), students & staff provide a tour to Governor Jay Inslee

SPECIFICATIONS

HULL TYPE & MATERIAL	Aluminum catamaran
RANGE	Inland waters of Puget Sound & Lake Washington
MAXIMUM SPEED	6.5 knots
LENGTH OVERALL	65'9"
BEAM	25'
DRAFT (LOADED)	3'2"
PROPULSION GENERATOR	125 kW, 480 AC, 60 Hz, 3-phase
SERVICE GENERATORS	25 kW, 240 VAC, 60 Hz, 3-phase
CRANE	Max capacity 5100 lbs
BUILDER	Craftsman United, Port Townsend, WA

ACOUSTIC TEST FACILITY

R/V *Russell Davis Light* now serves as APL-UW's acoustic test facility, which had been located on R/V *Henderson* prior to its retirement in 2020 following over 60 years of service. Electronics supporting acoustic measurements are located within the aft lab space adjacent to a moon pool and hydraulic ram. This equipment allows sensors to be lowered into the water and rotated during characterization tests of off-the-shelf and custom acoustic systems engineered at APL-UW.

RUSSELL DAVIS LIGHT

The research vessel was named to honor the late head of the Ocean Engineering Department at APL-UW, who passed away in 2018. Russ Light's career at APL-UW spanned 1982–2017, over which time he made significant contributions to electrical, software, and systems design of ocean-going instruments and platforms for basic and applied research applications. He also had an important role in modernizing much of the Laboratory's test infrastructure, including the acoustic test facility, which is now integrated on board R/V *Light*. Russ Light left an indelible mark on those who had the pleasure of working with him and it is fitting that such a capable vessel bears his name.

CROSS-FLOW TURBINES

Cross-flow turbines – vertical-axis turbines in the wind energy sector – have an axis of rotation perpendicular to the direction of moving water. This design has a number of strengths, including passive yaw control and relatively low rotation rates, which reduce radiated noise and animal collision risk. Their hydrodynamics are relatively complicated and, as a result, less well understood than for axial-flow turbines.

For cross-flow turbines to meet U.S. Navy needs, we need to understand their power generation potential and structural loading requirements. Because of their hydrodynamic complexity, cross-flow turbines are difficult to simulate, so our team chose to instead develop our understanding through laboratory experiments.

NAVFAC awards, augmented by the U.S. Department of Energy and the Alice C. Tyler Perpetual Trust, supported multiple graduate student researchers in the UW Department of Mechanical Engineering to develop new control schemes for cross-flow turbines, characterize the effects of turbine geometry for more than 200 unique combinations of turbine configuration and scale, and to understand, through additive manufacturing, the effects of hard fouling that could form on blades during an extended deployment. These sustained efforts advanced the fundamental understanding of cross-flow turbine hydrodynamics in the marine energy research community and provided APL-UW research staff with critical information used to design the Turbine-Lander system.

A 3D-printed laboratory-scale cross-flow turbine with blade fouling by barnacles. Blades with different fouling severity (barnacle size and density) were used to understand how turbine performance would change over time if fouling of this type occurred.

The Turbine-Lander design (p. 14) relies heavily on experience gained from laboratory-scale testing of cross-flow turbines. Students and engineering staff involved with this fundamental research supported analysis and provided feedback throughout the development period. Decisions informed by this research include load estimates and rotor/blade designs, both of which were used to maximize power production under the design constraints of the system. In addition, prior work suggested field-scale devices would require unique blade designs to resist buckling loads and stress concentrations at the tips of the blades. Subsequent analysis of the Turbine-Lander rotor and power take-off under propulsion using R/V *Russell Davis Light* show this lab-to-field collaboration resulted in a well-designed system.

Abigale Snortland (Mechanical Engineering Ph.D. student) and Greg Talpey (Mechanical Engineering Research Engineer) observing cross-flow turbine tests in the Alice C. Tyler flume at the Harris Hydraulics Laboratory. (Credit: Andrew Freeberg)

The U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) is advancing the commercial readiness of tidal and river current turbines through its Submarine Hydrokinetic And Riverine Kilo-megawatt Systems (SHARKS) program. Under SHARKS, UW was named the lead organization for a project that seeks to exploit the benefits of cross-flow turbine arrays that occupy a substantial portion of a channel's cross-sectional area. This project, which builds on foundational knowledge developed with NAVFAC support and involves APL-UW research staff, is demonstrating the possibility for turbine arrays to achieve efficiencies well above 100% by harnessing both the kinetic and potential energy in moving water.

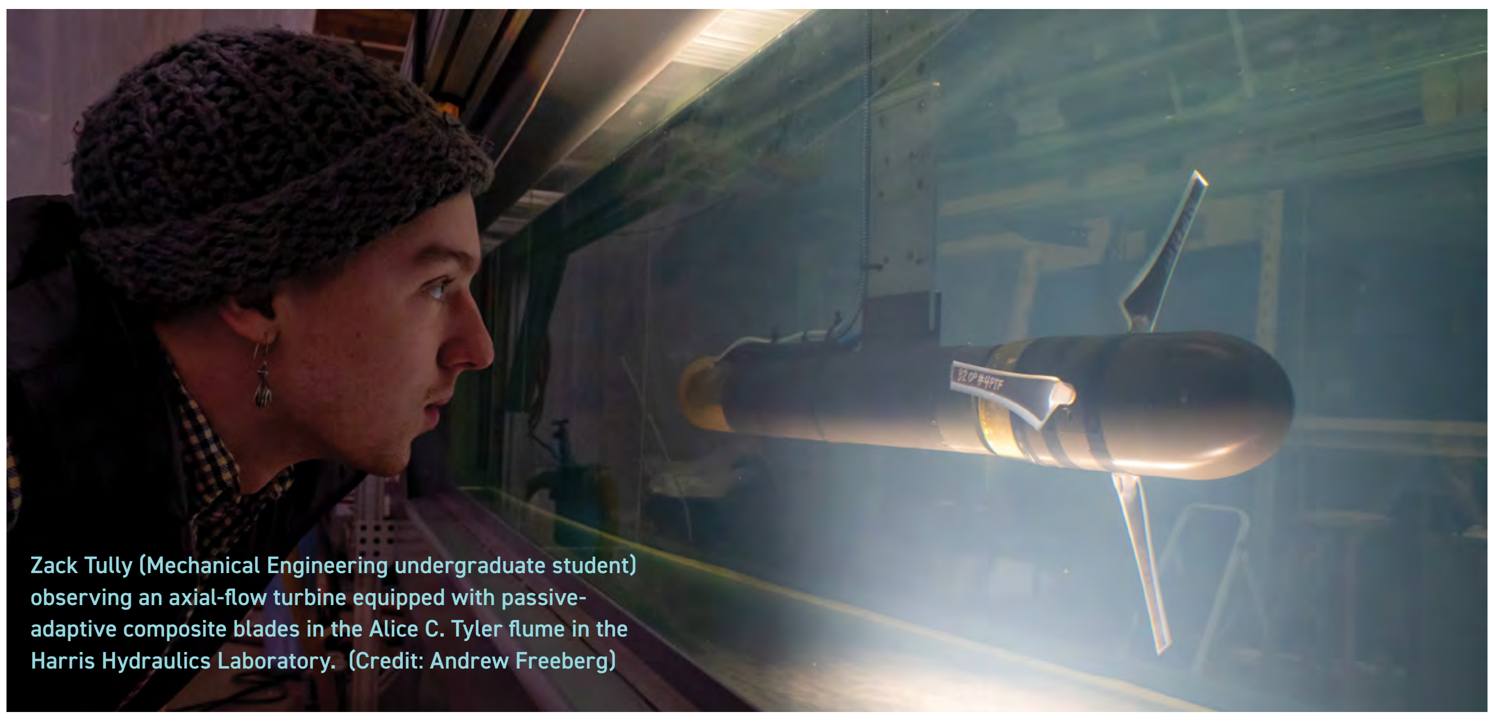
AXIAL-FLOW TURBINES

Axial-flow turbines – horizontal-axis turbines in the wind energy sector – are the largest marine turbines deployed to date. Individual axial-flow turbines have higher efficiencies than cross-flow turbines, but the most cost-effective designs incorporate active pitch control, which decreases reliability due to the potential for failures in the pitch servomotors.

One potential approach to increasing reliability without sacrificing performance benefits is to employ "passive" pitch control with composite blades that deform in an intentional manner under load. This allows the turbine to shed power and thrust in high currents, increasing survivability and decreasing cost.

APL-UW research staff collaborated with faculty and students in the UW Department of Mechanical Engineering to design a laboratory-scale turbine that could test this turbine control approach. Recent results show that "passive" pitch control is an effective control option for small-scale axial-flow turbines and establishes foundational knowledge about how to scale designs from the lab to the field.

Axial-flow turbines capable of harnessing water currents are being advanced by multiple federal agencies and private industry. APL-UW has completed fabrication of a 1-m diameter axial-flow turbine and installed the unit on R/V *Russell Davis Light* for open water tests. Ongoing work with the unit will address translation of passive-adaptive control to larger scales and axial-flow turbine performance in off-axis flow. We anticipate opportunities to collaborate with U.S. Department of Energy national laboratories to leverage this field capability.



Zack Tully (Mechanical Engineering undergraduate student) observing an axial-flow turbine equipped with passive-adaptive composite blades in the Alice C. Tyler flume in the Harris Hydraulics Laboratory. (Credit: Andrew Freeberg)

A key challenge with this type of research, which was also encountered in the design of the cross-flow Turbine-Lander (p. 14), is that material strength is an intensive property that does not change with physical scale. As a result, a laboratory-scale composite blade that produces desired deformation behavior would be much too flexible to be used in a larger turbine. A team of researchers from the UW Mechanical Engineering and Civil and Environmental Engineering departments have collaborated for several years to advance our understanding of this challenge and how to address it in the design of field-scale axial-flow turbines.

LAB-TO-FIELD TURBINES

While laboratory-scale research is critical to understanding basic rotor hydrodynamics and for predicting anticipated power generation and loads in field-scale devices, such work cannot replace field-scale testing. Tanks are inherently restricted environments and cannot effectively replicate all forcing encountered by field-scale devices. Numerous experiments leveraging turbines with different designs have been performed to study field-scale device performance and to test concepts previously studied in the laboratory.

Field-scale coordinated control

Prior lab-scale research in confined flows showed that by coordinating the control of two closely-spaced rotors the total power extracted can be increased. Similar results had not been demonstrated at field scales so testing was performed using two Turbine-Lander units (rotor and power take-off) installed on R/V *Russell Davis Light.* Analysis is ongoing but suggests that it may be possible to achieve incremental increases in power extraction from coordinated control at field scales. These gains, however, are generally lower than in laboratory studies due to the unconfined nature of the flow.

Turbine-Lander testing

The four-bladed Turbine-Lander rotor (p. 14) geometry and hydrofoil design were selected based on laboratory measurements to optimize power extraction within the bounds of other design constraints including hydrodynamic torque and thrust limits. The Turbine-Lander's rotor and generator have been characterized under propulsion and in a moored configuration. Overall, the peak water-to-wire efficiency is approximately 25%, indicating efficient mechanical power extraction from available currents.

Two rotors installed on R/V *Light* for coordinated control testing. In this case, rotors were installed with only two blades. The two rotors were also tested without blades to quantify losses associated with the struts and central shaft while dynamometer measurements were performed to better understand losses associated with motor/generator efficiency and the bearing pack.

The Turbine-Lander rotor (and VAMP) mounted on R/V *Light* prior to its deployment in Agate Pass.

Axial-flow turbine installed on R/V *Light* for testing under propulsion. The rotor is approximately 1 m in diameter and the unit is equipped with multiple 6-axis load cells to measure loads and system performance.

Axial-flow turbine

A field-scale version of the axial-flow turbine has also been fabricated and tested on R/V *Light*. This system is currently being used for general rotor characterization and to study field-scale passive adaptive blades. The completion of the axial-flow turbine is relatively new and work with the system is ongoing.

miniWEC

APL-UW developed a simple point absorber wave energy converter, the miniWEC, as a platform to test hydrodynamics and power take-off (PTO) control strategies. The miniWEC has been used in two Joint Industry Projects: as a platform to test the impact of heave plate geometries on WEC performance (a collaboration with CalWave), and to test the impact of active control strategies (a collaboration with Oscilla Power).

The miniWEC during tests on Lake Washington

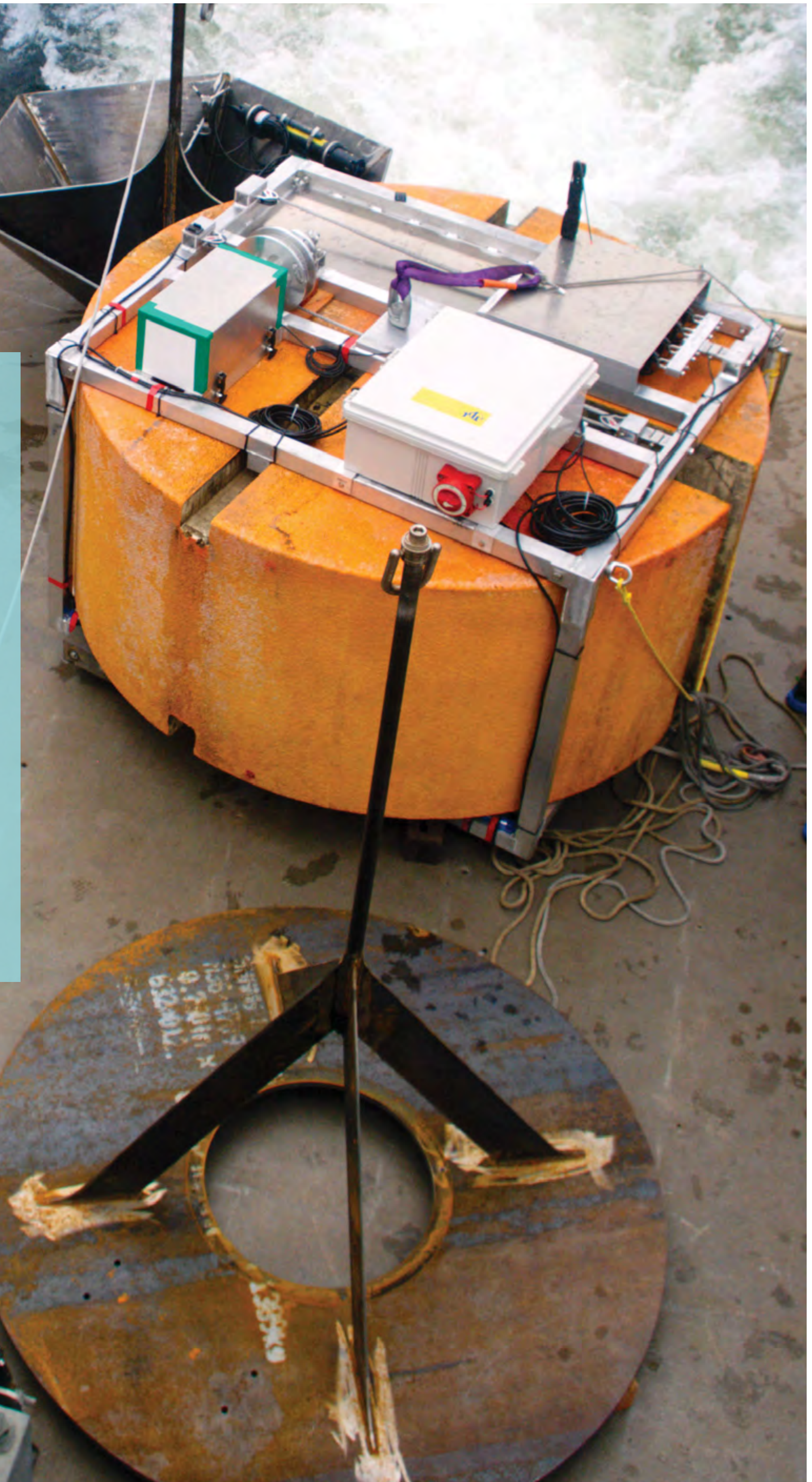
The miniWEC in calm water with controlled boat wakes

Joint industry projects

The projects centered on the miniWEC were productive collaborations and serve as models for future projects with industry. This work brought together the engineering capabilities of APL-UW, UW Mechanical Engineering staff and graduate students, and industry partners with research questions directly applicable to their technologies.

With CalWave, a wave energy company based in Berkeley, CA, we assessed the impact of a range of geometric parameters on heave plate hydrodynamics. Initially, the hydrodynamics of thirteen different heave plates were assessed at a small scale using APL-UW experimental facilities. From these results, three heave plates were selected for testing at a large scale with the miniWEC. In this phase, each plate was deployed with the miniWEC to assess the plate's impact on the behavior of the full system. Data and lessons learned from these tests informed student research at UW and helped CalWave to evolve their WEC design.

With Oscilla Power, Inc., a wave energy company in Seattle, WA, we assessed the benefit of active controls on WEC performance using simulations and the miniWEC in the field. A UW graduate student collaborated with engineers at Oscilla Power to develop simulations of the miniWEC to assess proposed active control strategies. Promising control schemes from simulations were then implemented on the miniWEC with the help of UW Mechanical Engineering and APL-UW staff. These control strategies were tested in natural waves and their effect on system performance analyzed. Oscilla Power has used these results to inform the development of control algorithms for their Triton-C WEC, which has three PTOs (the miniWEC has one).



Field testing

The miniWEC was deployed during 6-hour periods to drift on Lake Washington and Puget Sound in 2016, 2017, and 2018. In addition to the Joint Industry Project tests, more were conducted to validate the hydrodynamics of hexagonal conic and flat heave plates, both with and without holes at their base. During field testing, SWIFT drifters developed at APL-UW were deployed with the miniWEC to measure the wave field throughout each test. These data were used to test algorithms for real time reconstruction of the wave forcing on a WEC, a technique being employed for WEC-UUV (pp. 16-17) deployments.

The miniWEC on the deck of R/V *Robertson* during tests of flat and conic heave plates

HEAVE PLATE HYDRODYNAMICS

Point absorber wave energy converters generate power from the relative motion between a surface (or subsurface) float and reaction surface. In shallow water this can be the seabed, but in deeper water this is impractical, so heave plates are often used. Heave plates generate high inertia when accelerated and can provide necessary reaction forces in any water depth.

Motivation

In our early research on wave energy converter (WEC) design and performance, we discovered a gap in the literature regarding WECs that utilize a heave plate. Specifically, numerical simulations of WEC performance were limited by unknowns in heave plate hydrodynamics. Force on a flat heaving plate is well characterized for relatively small-amplitude motions, but was not well known for larger-amplitude motions or for heave plates with asymmetric geometries. To model WECs with a heave plate accurately, we characterized the hydrodynamics and how they scale across a range of conditions and heave plate geometries relevant to wave energy.

Laboratory testing

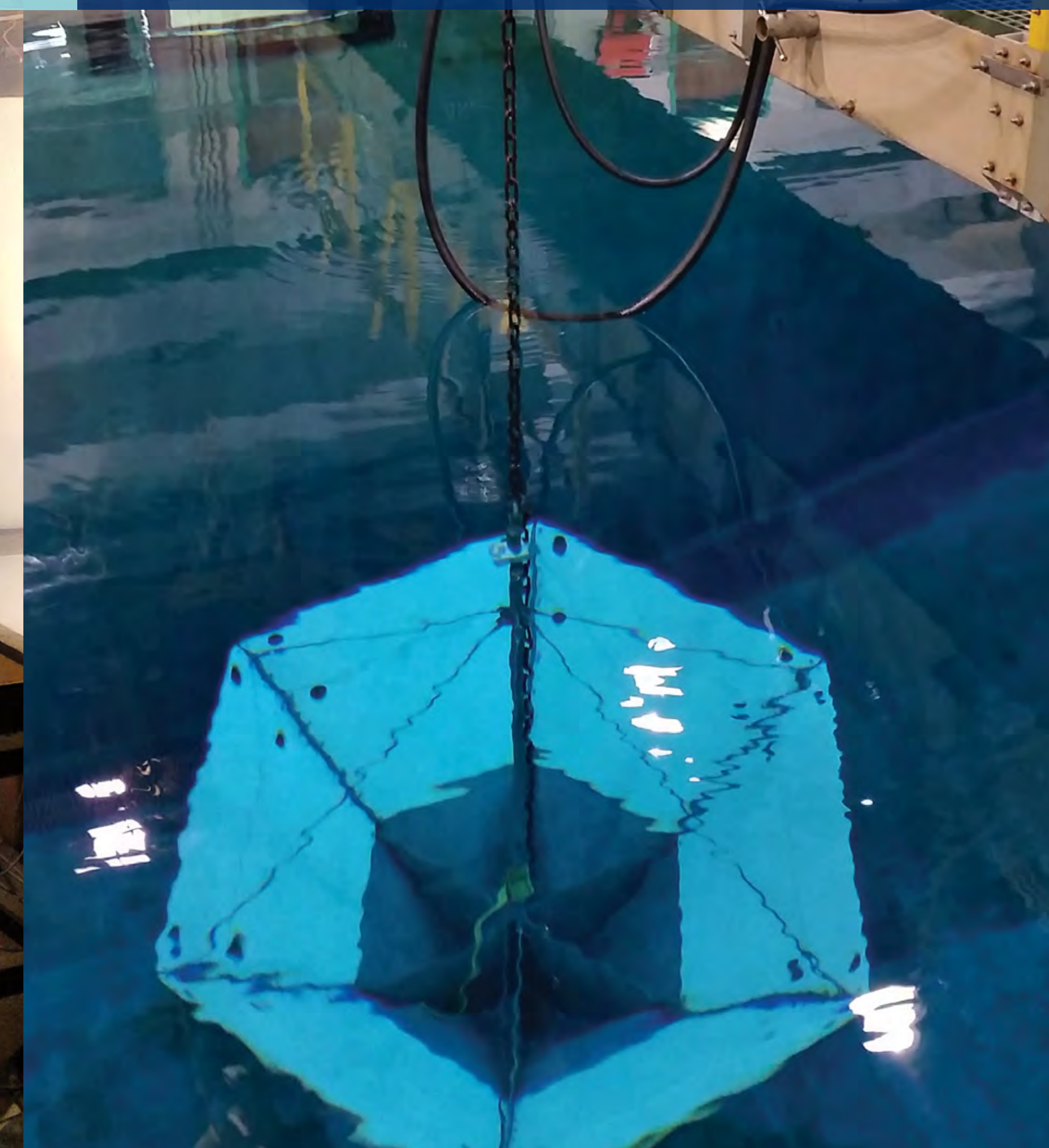
With no analytical method or simulation to model the complexity of this problem confidently, we used laboratory testing to investigate the relationships between heave plate scale, geometry, and hydrodynamic force. For a hexagonal conic plate, we tested heave plates with diameters of 0.27 m, 0.54 m, and 2.72 m at the UW flow visualization tank, at the APL-UW dock on Portage Bay, and at the Monterey Bay Aquarium Research Institute. We found that the coefficients of drag and added mass scale with the Keulegan–Carpenter (KC) number. Further tests assessed the impact of enclosing a hexagonal conic plate on its hydrodynamic reaction force, and revealed that an open conic produced a greater reaction than an enclosed one. This information allows us to make much more accurate estimates of WEC power output and structural forces.

Key findings

- Drag and added mass coefficients for asymmetric heave plates scale with KC
- Heave plate coefficients scale with KC for $0 < KC < 7$, covering a wide range of environmental conditions
- Counterintuitively, enclosing a hexagonal conic plate decreases its reaction force compared to flat and open hexagonal conic plates
- The use of experimentally-derived added mass in WEC models yields large changes (> 100% difference) in estimated WEC power output when compared to added mass calculated according to hydrodynamic simulations

Three heave plate geometries tested in the UW flow visualization tank: a flat hexagonal plate, an enclosed hexagonal conic, and an open hexagonal conic (left to right)

Scaled hexagonal conic plates with diameters of 0.27 m, 0.54 m, and 2.72 m (left to right)



UW flow visualization tank (left), where experiments with 0.27 m diameter heave plates were conducted, and the MBARI test tank (right) with the 2.72 m diameter heave plate during experiments.

TURBINE-LANDER

Our team's objective is to develop a tidal turbine system capable of generating 100+ W (average) to support remote power applications in areas with strong tidal currents. The solution is a Turbine-Lander with a ~1 m^2 (swept area) cross-flow turbine and all supporting power electronics on a bottom lander structure. The lander is instrumented with an environmental monitoring package (AMP, pp. 20-21) to address key uncertainties regarding environmental impacts, such as collision risk for marine animals.

Benefits

The Turbine-Lander system is designed to produce predictable amounts of power from currents in remote areas that lack cabled infrastructure. Power generation is ultimately dependent on site-specific conditions, and the Turbine-Lander is designed to generate power when currents are between approximately 1-2.5 m/s. The current housings are designed for deployments to depths up to 60 m.

System development & testing

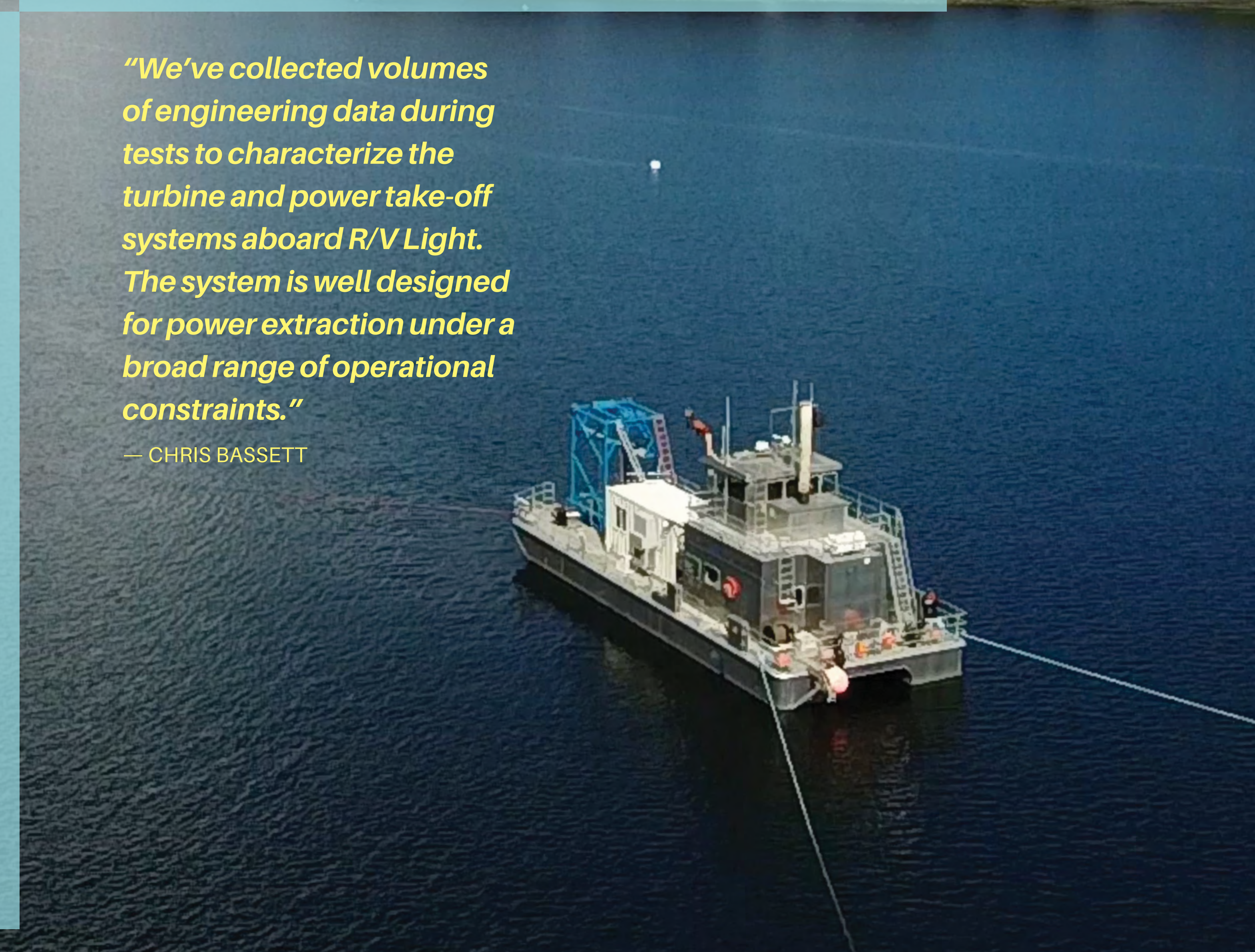
Vessel-based testing of the Turbine-Lander power take-off (PTO) and rotor were performed in 2021 and 2022 on R/V *Russell Davis Light*. This included deployment for seven days from R/V *Light* while moored in Agate Passage, WA, in April 2022. Water-to-wire efficiencies vary with inflow velocities due to losses in components like the seals and generator. However, peak efficiencies, defined as the proportion of available mechanical power converted to electric power, are approximately 25%. This corresponds to peak power production exceeding 1 kW for currents at a rated speed of 2.5 m/s.

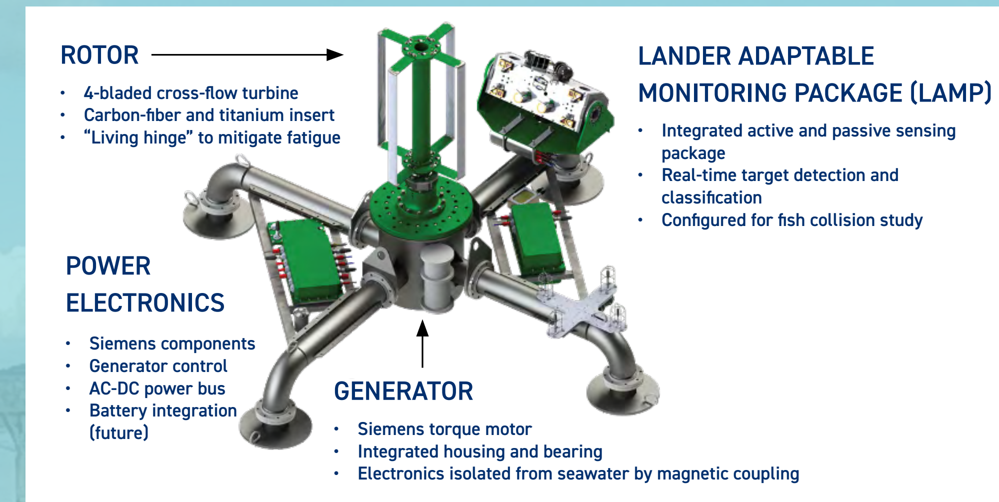
Endurance tests of the Turbine-Lander PTO and rotor at the Pacific Northwest National Laboratory Marine and Coastal Research Lab in Sequim, WA, is expected in fall 2023. Ongoing work will support the transition to autonomy by replacing AC power cables to the PTO with a battery bank, in addition to improving system efficiency by decreasing losses and internal power consumption.

SPECIFICATIONS

WEIGHT IN AIR	2350 kg (5180 lbs)
NET WEIGHT IN WATER	1670 kg (3680 lbs)
CUT-IN SPEED	1 m/s (1.94 knots)*
ROTOR EFFICIENCY	~35%
GENERATOR EFFICIENCY	~80%
PEAK POWER PRODUCTION	1 kW

*With ongoing system improvements to decrease frictional losses being investigated under current funding, this value may drop to as low as 0.75 m/s.





Harlin Wood and Chris Bassett with the Turbine-Lander's rotor and hub during the first assembly.

"We've collected volumes of engineering data during tests to characterize the turbine and power take-off systems aboard R/V Light. The system is well designed for power extraction under a broad range of operational constraints."

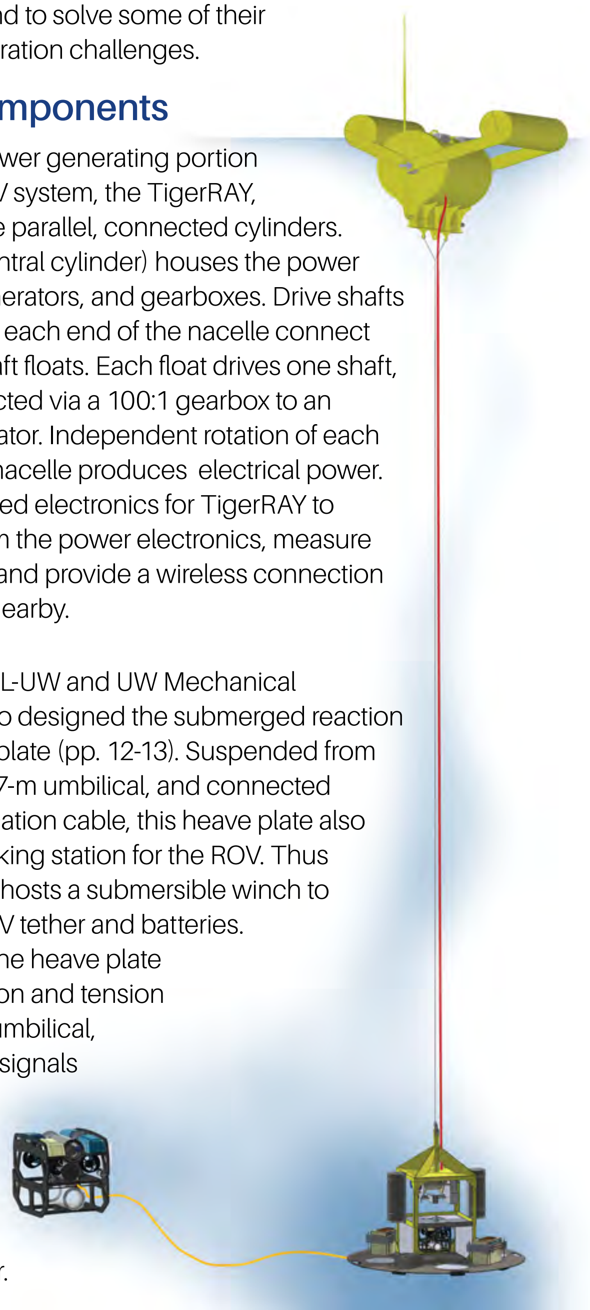
— CHRIS BASSETT

The WEC-UUV system combines a wave energy converter (TigerRAY, by CPower) with an uncrewed underwater vehicle (BlueROV2, by BlueRobotics). The UUV charges from the WEC while inside a docking station that is integrated with the subsurface heave plate. When an operator is within range of the WEC, the UUV can be operated via Wi-Fi. This project aims to demonstrate the potential of paired WEC-UUV systems and to solve some of their design and operation challenges.

System components

The floating, power generating portion of the WEC-UUV system, the TigerRAY, consists of three parallel, connected cylinders. The nacelle (central cylinder) houses the power electronics, generators, and gearboxes. Drive shafts protruding from each end of the nacelle connect to the fore and aft floats. Each float drives one shaft, which is connected via a 100:1 gearbox to an electrical generator. Independent rotation of each float about the nacelle produces electrical power. UW staff designed electronics for TigerRAY to collect data from the power electronics, measure device motion, and provide a wireless connection to researchers nearby.

Engineers at APL-UW and UW Mechanical Engineering also designed the submerged reaction body, or heave plate (pp. 12-13). Suspended from the WEC by a 27-m umbilical, and connected via a communication cable, this heave plate also serves as a docking station for the ROV. Thus the heave plate hosts a submersible winch to manage the ROV tether and batteries. Electronics on the heave plate monitor its motion and tension in the strength umbilical, provide control signals to the winch and ROV, and provide video streams from the ROV to the vehicle operator.



Schematic of the WEC-UUV system, which consists of the TigerRAY WEC at the surface, connected to a heave plate at about 27 m depth, which houses the BlueROV2, and a submersible winch to manage the ROV tether.

"We are building the capability to deploy power-intensive oceanographic instruments for months to years without human intervention."

— CURTIS RUSCH

Dynamometer testing of the WEC-UUV system at APL-UW, January 2023. This is an important step to de-risk field deployments.

Timeline

Design and fabrication of the WEC-UUV began in late 2019. In fall 2021, the heave plate docking station was tested with the BlueROV2. TigerRAY was delivered to APL-UW in early January 2022 and put through initial dynamometer testing before the first round of drifting field tests in winter 2022. System electronics were upgraded to improve performance in summer 2022, and a second round of dynamometer testing was conducted in late 2022.

Additional drifting field tests were conducted in February 2023 and substantial improvements to power generation were verified. A one-month moored deployment of the system is planned for winter 2024.

System development & testing

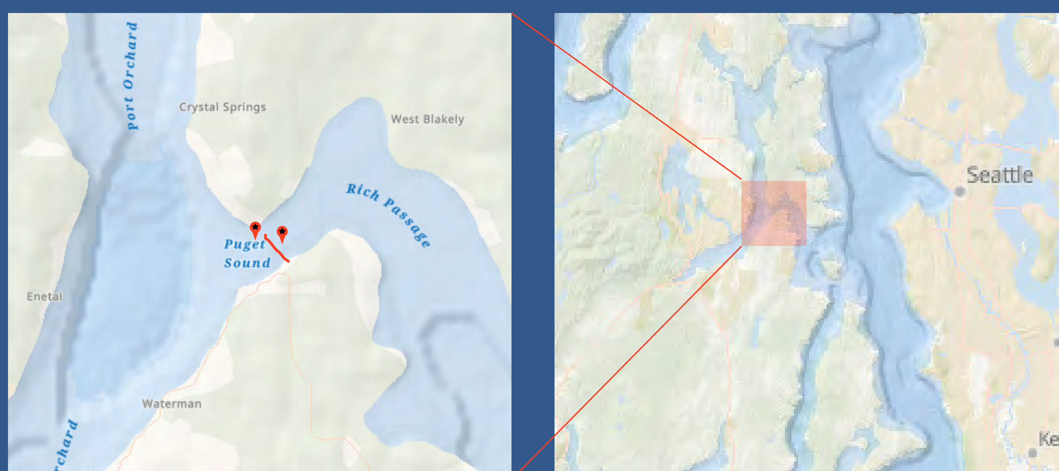
Prior to each round of field tests, the APL-UW dynamometer was used to test TigerRAY's generators and power electronics. These tests tuned the system's control inputs, characterized friction, and studied the relationships between torque and shaft speed.

Drifting field tests have been used to collect data from the system when in flat water, in calm seas with controlled boat wakes, and in natural wind-driven waves. Data are used to assess system performance, to make improvements for future tests, and to validate hydrodynamic models. Four Surface Wave Instrument Float with Tracking (SWIFT) buoys, designed and built by APL-UW, are deployed with TigerRAY to measure the waves incident on the WEC. The wave measurements provide important context for TigerRAY's power generation.

Previous ROV piloting has been conducted during periods with calm conditions. All six attempts to dock the ROV have been successful, and the ROV was used to inspect the heave plate and lower portion of the strength umbilical.

SITE CHARACTERIZATION

The successful conversion of marine renewable energy requires detailed knowledge of the conditions at each proposed site. This is essential to achieve high efficiency during benign conditions and for survivability during extreme conditions. APL-UW has been developing and demonstrating methods for site characterization in wave and current energy environments for over a decade. Two recent studies applying these characterization techniques were performed at sites of relevance to the Navy.



Rich Passage location and the measurement sites.

Currents in Rich Passage

Rich Passage (WA) is a narrow channel that connects the main basin of Puget Sound to the Naval Station at Bremerton (now part of Naval Base Kitsap). APL-UW collected measurements of the tidal currents through this passage using acoustic Doppler current profilers (ADCPs) deployed on the seafloor. In addition to determining the standard metrics for mean currents and kinetic power density, a new method to quantify the turbulence profiles at the site was developed by a Ph.D. student and her APL-UW advisor. The turbulence method utilized recent improvements in ADCP technology: a 5th acoustic beam and reduced measurement noise in the Doppler processing. APL-UW introduced a novel method to obtain ground-truth measurements for the new turbulence data using a high-precision velocimeter suspended from a research vessel and a data processing technique to remove vessel motion.

Seafloor tripod with 5-beam ADCP deployed in Rich Passage. Maricarmen Guerra developed the 5-beam turbulence methods as part of her Ph.D. dissertation (completed in 2019).


APL-UW staff readying a moored wave buoy for deployment near San Nicolas Island.

Waves at San Nicolas Island

San Nicolas Island (CA) is a naval facility approximately 61 miles off the coast of southern California. APL-UW collected measurements of the ocean surface waves around the island by adding a moored wave buoy to the existing network of buoys maintained by the Coastal Data Information Program. In addition to calculating the standard metrics for wave climate and power density, APL-UW demonstrated a new wave steepness criterion to limit the extrapolation from a given wave climate to extreme conditions. This method can be extended to other sites, where long time series measurements are not available to assess the suitability of wave converter designs.

San Nicolas Island and moored wave buoy sites. APL-UW collected data at Site 138 during 2015–2017.

OTHER RESOURCE ASSESSMENT

UW marine energy researchers have performed numerous site-specific resource assessments and have made notable methodological contributions for both tidal and wave energy. Supported by other sponsors, UW researchers have performed tidal resource characterization in Admiralty Inlet and the San Juan Islands (Salish Sea) and have performed current and turbulence measurements elsewhere in Washington and the Canal de Chacao (Chile). The products of this research have resulted in well cited manuscripts on characterization and methodology that continue to inform project siting and turbine design.

ADAPTABLE MONITORING PACKAGE

A team of UW engineers has developed technology to facilitate integrated environmental monitoring around marine energy converters. The Adaptable Monitoring Package (AMP) backbone is a modular hardware/software architecture that allows operation and control of a variety of sensing systems — cameras, passive and active acoustic sensors, current profilers — from a single interface, making possible cooperative processing and management of high-bandwidth data streams.

Recent development efforts include integrating AMP with the Turbine-Lander and powering its sensing payload with tidal currents. In total, including field and vessel-based deployments, AMPs have accumulated more than one year of operations with over 95% uptime system availability with another year or more of planned operations at wave and tidal energy sites with wave and tidal energy converters.

AMPs with various sensor, power, and control configurations have been deployed in a range of ocean environments. The team has gained knowledge on biofouling and corrosion, sensor performance across environments and deployment modes, and the effectiveness of automated detection and classification algorithms that enable continuous observations without accruing prohibitively large volumes of data.

WAMP

A wave-powered AMP (WAMP) was integrated with the Fred. Olsen BOLT Lifesaver wave energy converter and deployed at the U.S. Navy's Wave Energy Test Site for six months. WAMP was powered by the WEC, backed up by a 525 Ah 24VDC battery bank, and was operational 85% of its deployment time.

VAMP

A vessel-based AMP (VAMP) iteration decouples package systems and mounts them on R/V *Russell Davis Light* (pp. 4-5). In a typical scenario the VAMP provides real time stereo optical imagery of rotors and supports processing and communication of the measured inflow speed for turbine control.

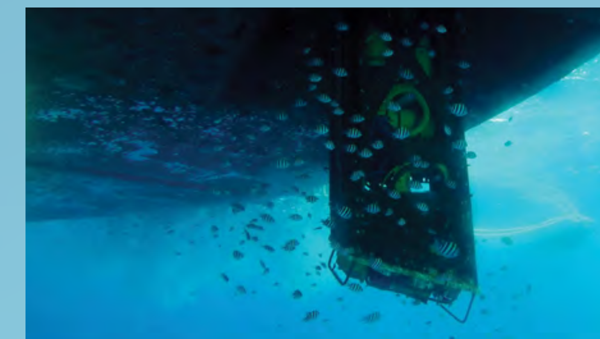
LAMP

The lander AMP (LAMP) iteration is designed specifically to integrate with the Turbine–Lander (pp. 14-15). In addition to standard AMP capabilities, it includes a second imaging sonar. The sonar pair can image acoustically a large field of view around the Turbine–Lander rotor to study fish interactions with the device and track their paths up and downstream.

Future applications

While the AMP has not yet been deployed for purposes other than marine energy, the technology could be deployed in support of other science or national security (e.g., harbor security).

The WAMP prior to deployment on the Fred. Olsen BOLT Lifesaver



Fish aggregating near the WAMP during operations

THE AMP TECHNOLOGY IS BEING COMMERCIALIZED (P. 26)

"Development first concentrated on hardware and instruments, then moved to software engineering to ensure all sensors would work without interference. Finally, we've focused on smart data control and processing to accomplish automatic target detection, tracking, and classification."

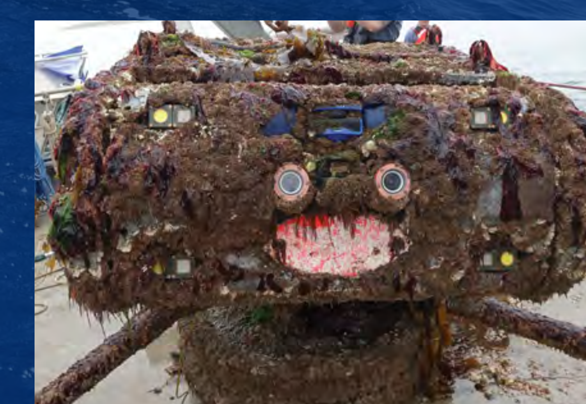
— JAMES JOSLIN

The AMP before deployment in Sequim Bay

DEPARTMENT OF ENERGY SUPPORT FOR AMP

An AMP is currently installed on the Oscilla Triton-C wave energy converter with an anticipated deployment/monitoring period of one year. By observing the WEC's hull, tethers, and heave ring we anticipate results focused on animal presence/absence, entanglement risk, and sediment accumulation. In addition, a long-term near-field data set of radiated noise from the WEC is being collected at the U.S. Navy's Wave Energy Test Site in Hawai'i.

The LAMP is being leveraged with support from DOE to investigate the risk of collision of fish with rotating tidal turbines. Optical cameras detect animals and the rotor in the near field, while multiple imaging sonars will track targets in the vicinity.



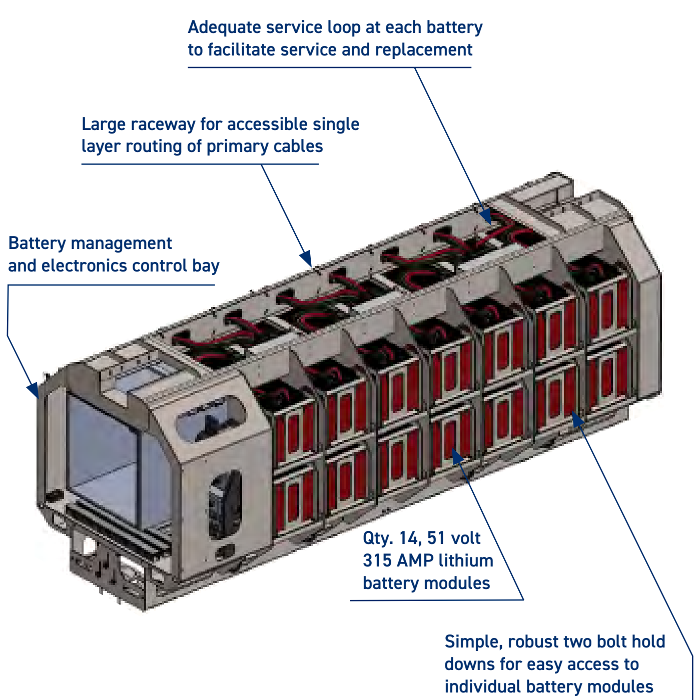
The AMP following a 118-day deployment (96% system availability) in Sequim Bay

SEAFLOOR POWER VAULT

Objective

In collaboration with Oregon State University (OSU), APL-UW is developing the Seafloor Power Vault (SPV) – a 225 kWh rechargeable battery in a one-atmosphere titanium housing with steel foundation that can be deployed at depths up to 100 m.

This project has two goals: to demonstrate the ability to reliably charge a large battery on the seafloor from a standalone power generator such as a wave energy converter (WEC) or a tidal turbine, and to demonstrate the ability to distribute that stored energy to peripheral users such as a charging dock for uncrewed undersea vehicles (UUVs).



Benefit

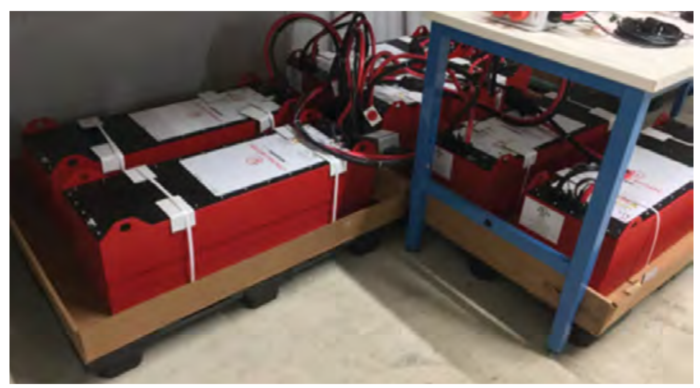
The technology for subsea microgrids – isolated power generators connected only to local users – remains in an early stage of development. The Navy has an interest in this technology, but few other examples of similar technology exist. The SPV will be reconfigurable to accommodate different power sources and users, and will be robust, allowing sequential deployments in many locations. A key function of the SPV is to support the development of autonomous charging of UUVs. The maximum allowable charge and discharge rates are 3.6 kW and 45 kW, respectively, although either rate may be limited by the capabilities of the connector and cable systems.

System development & testing

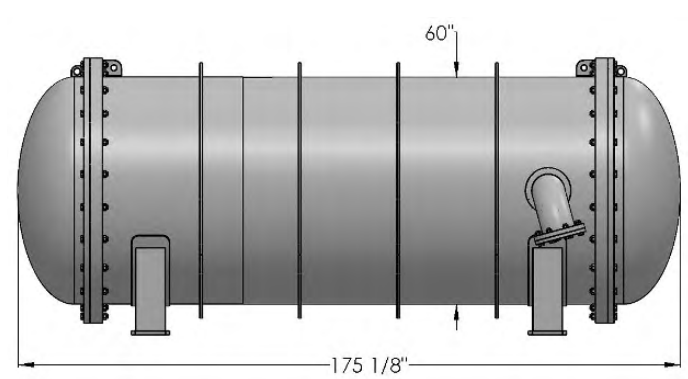
Deployment of the first SPV is scheduled for late summer 2024. Initial testing will exercise the system via a trunk cable from shore to most efficiently charge and communicate with the SPV. Relatively minor modifications will then allow the SPV to be reconfigured for charging from a marine energy converter.

OSU is responsible for the battery, battery carriage (the internal support structure), and power management. APL-UW is responsible for the housing, foundation, the engineering sensor system, deployment, and recovery.

The battery comprises 14 lithium iron phosphate modules from Lithionics Battery with a dedicated battery management system to maintain optimum system health. All modules have been received by OSU and carriage construction is underway.



The housing design is complete and was put out for bid at the end of 2022. Design and construction of the steel foundation will follow selection of the initial test site. Design of the engineering sensor system is also underway. System integration will be completed at OSU, after which the SPV will be transported to the chosen deployment location for at-sea testing.



ROV AUTONOMOUS INSPECTION

Objective

Once deployed, marine energy converters will require inspection and maintenance to ensure reliable long-term operation. Because these will be located far from shore and operating in environments with strong currents, waves, and tides, regular inspection by divers will be expensive, time-consuming, and potentially dangerous. Instead, autonomous robotic systems can be installed near or as part of marine energy converters to perform remote inspection and repair of systems in place. These robots may be controlled remotely by support crew on shore, or may use onboard intelligence to inspect the marine energy system autonomously, sending a full report to shore once completed, or alerting human operators in the event of a serious problem.

Advancing this vision of autonomous robotic support for marine energy requires the development of robots designed to collect meaningful inspection data and algorithms to sense, plan, and act to complete inspection missions. In collaboration with the Oregon State University Collaborative Robotics and Intelligent Systems (CoRIS) Institute, APL-UW is working to achieve this vision through the development of a new subsea robot and sophisticated perception and path planning algorithms.

Raven system development

The Raven ROV was developed as a unique platform to test novel perception sensors and robotic autonomy algorithms. It is a tethered system, powered by a support ship. This tether also carries a 10-GB data connection between the vehicle and operators on the ship, giving a real time stream of ROV sensor data. The platform accelerates the development and testing of the robotic sensing and control tools required for autonomous operations.

SPECIFICATIONS

SIZE	L 58" x W 36" x H 31"
WEIGHT	380 lbs (in air)
ENVIRONMENT	0-100 m
LOCALIZATION	IMU, 1 MHz ADCP/DVL, GPS (at surface)
SENSING	Stereo 5 MP machine vision cameras, 1.2/2.1 MHz imaging sonar

To navigate safely around a marine energy converter, the ROV uses a combination of stereo machine vision cameras and a high-frequency imaging sonar. At short ranges the stereo cameras provide detailed data on the state of the converter, while at longer ranges the sonar can be used to observe and track the converter even in highly turbid water. The vehicle uses GPS to navigate (when on the surface) and an inertial measurement unit and Doppler velocity log to track its position (when underwater). Designed to operate in energetic environments, it carries 11 thrusters – eight operating horizontally, to make way against strong currents, and three vertically, for active pitch and roll control.

Robotic autonomy

The Raven vehicle operates on software alone, without a human in the loop. A low-level control system is provided by Greensea Systems and from this base, researchers at Oregon State University and APL-UW have built a complete robotic autonomy control system in the Robot Operating System (ROS). This consists of software to locate and map a marine energy converter using the high-frequency imaging sonar, to plan effective trajectories to observe the converter from all sides, and to convert those plans to safe, achievable motions.

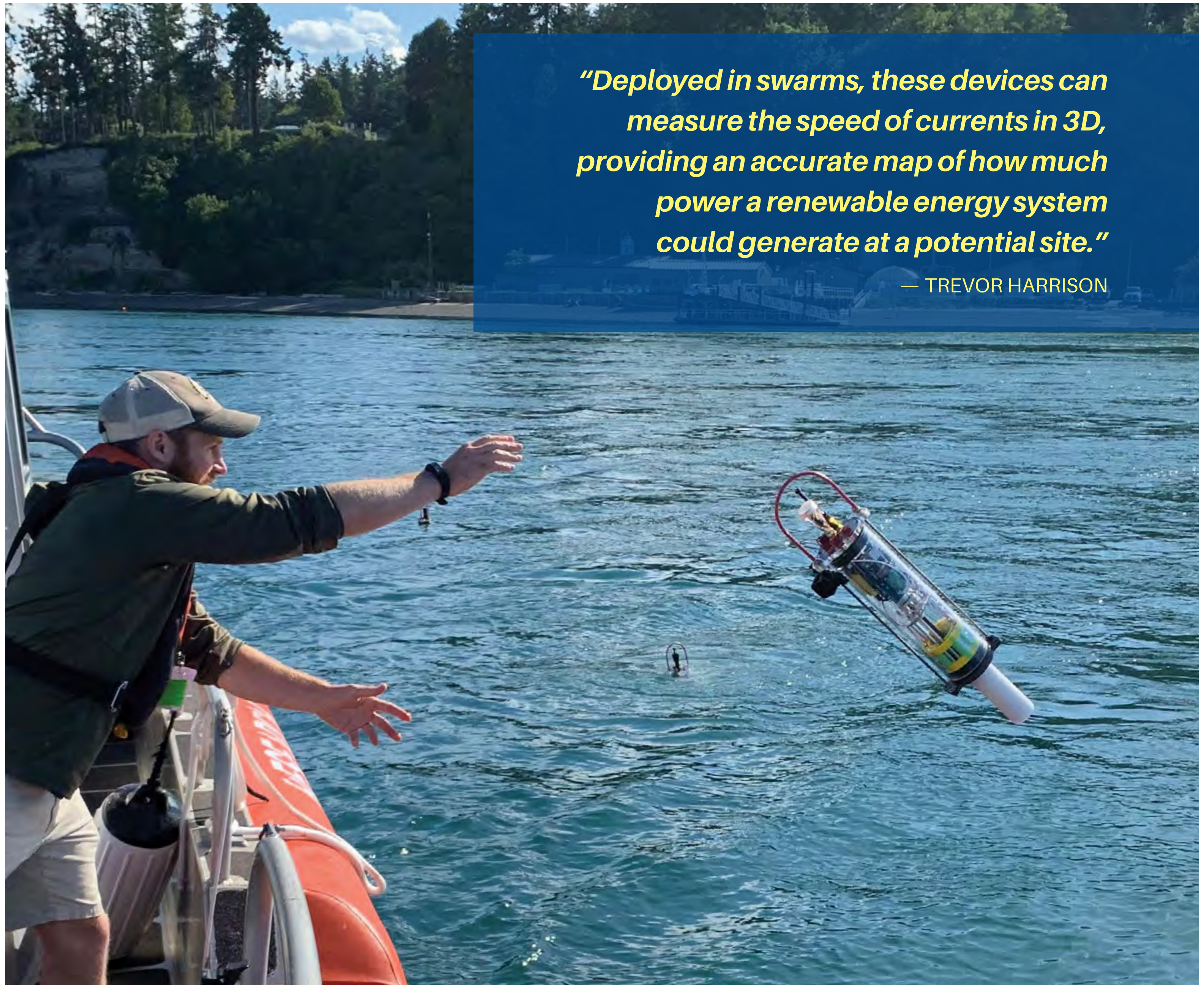
Testing

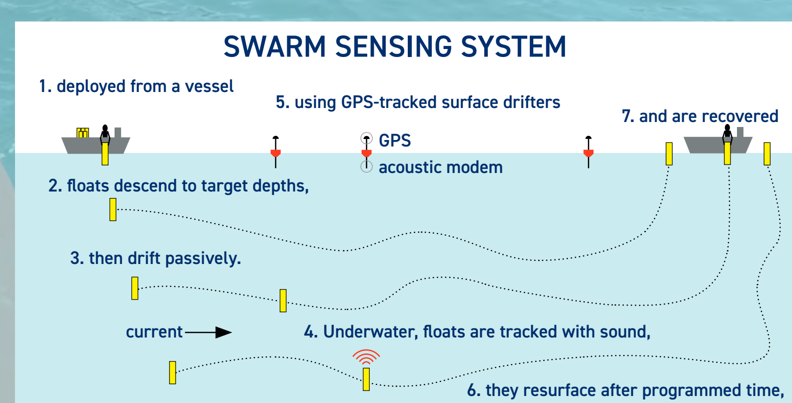
Raven was commissioned in February 2022 and completed multiple tests on Lake Washington throughout the year, operating from R/V *Robertson*. Early tests focused on refinement and tuning of the vehicle's control system, as well as testing the link between the vehicle autonomy/path planning software and the lower-level trajectory and dynamic control systems. Later cruises collected sample data with the ROV's cameras and sonar to evaluate perception algorithms.

Because of its flexible sensor payload, the Raven is an essential asset to test robotic sensors and hardware quickly at APL-UW.

"Deployed in swarms, these devices can measure the speed of currents in 3D, providing an accurate map of how much power a renewable energy system could generate at a potential site."

— TREVOR HARRISON



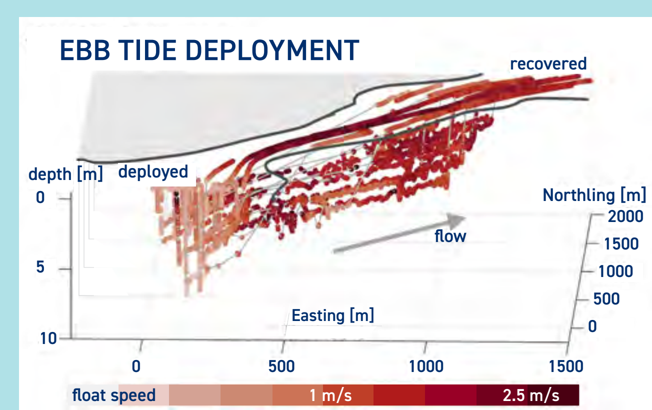


Objective & capabilities

UW students and staff have developed a buoyancy-controlled underwater drifting sensor platform for distributed sensing in littoral waters. The µFloat buoyancy engine provides autoballasting from fresh to salt water and depth control within ±0.5 m in energetic environments. µFloats are equipped with GPS for positioning while on the surface and can be tracked acoustically while under water using an array of localization buoys that send coordinated "pings" to the floats, providing absolute geographic position within ±5 m horizontal. The base sensor suite includes pressure, temperature, and an inertial measurement unit. Surface communications include 900 MHz radio, a cellular link, and 2.4 GHz Wi-Fi.

Timeline

Development began in early 2016, with the first prototype designed and built by a senior undergraduate mechanical engineering capstone team. A second version was fabricated and tested in 2017. Office of Naval Research Defense University Research Instrumentation Program funding was received in 2017 to manufacture a swarm of 30 floats. In 2018 we overhauled the design to improve manufacturability and performance. Preliminary evaluation deployments were performed in 2019 in Lake Washington and Sequim Bay, WA. The first full swarm deployment in Agate Pass, WA, was carried out to map tidal currents. In March 2023, subsequent uFloat tests were performed at the mouth of the Snohomish River, WA to demonstrate upgraded acoustic modem performance, and buoyancy control – including new depth control algorithms – in stratified waters. Combined with prior deployments, over 600 individual deployments and recoveries have been completed to date.



Future applications

We have recently integrated a conductivity sensor into the floats so they can map density and sound speed. The acoustic modems used in localization have been upgraded to provide faster and more robust positioning as well as bidirectional communications. Future work will focus on developing µFloats equipped with hydrophones to volumetrically map ambient and anthropogenic noise.

SPECIFICATIONS

SIZE	Length: 72 cm; Diameter: 12 cm
WEIGHT	4.9 kg
ENVIRONMENT	Depth: 0-100 m; Horizontal range: 10 km Temperature: 0-60°C
POWER	Source: 96 Wh rechargeable lithium-ion batteries Consumption: 3.5 W Endurance: 1 day with base sensor suite
ACTUATION	Buoyancy control: ±5% total volume change Depth control: ±0.5 m accuracy Terminal velocity: 0.6 m/s
LOCALIZATION	Surface: GPS, +2.5 m accuracy Underwater: Acoustic nanomodem, long baseline, ±5 m accuracy, 1000 m range and ±1 m depth accuracy
ELECTRONICS	Beaglebone Black with Linux (1 GHz ARM Cortex-A8) 32 GB Memory, 512 MB DDR3 RAM
MEASUREMENTS	Pressure: 0-100 dbar, ±3% total error band Temperature: -40-125°C range, ±0.5°C accuracy Inertial measurement unit (IMU) Internal condition monitoring: voltage, current, temperature, pressure, and relative humidity Auxiliary port for external sensors

COMMERCIALIZATION & INDUSTRY COLLABORATIONS

MarineSitu, Inc. was founded in 2016 as a UW spin-off company to transition the AMP (pp. 20-21) hardware and software from the laboratory research prototypes to commercial products. In 2021 MarineSitu received Department of Energy Small Business Innovation Research support to further develop and test a modular stereo-optical camera system with autonomous target detection and classification software. MarineSitu has subsequently received Phase II support for ongoing commercialization efforts related to the AMP. In 2023 MarineSitu anticipates launching its first AMP-related commercial products.

MarineSitu

Benjamin Strom co-founded **XFlow Energy**, a vertical-axis wind turbine technology developer, after graduating with a Ph.D. from the University of Washington in 2019. As a student, Dr. Strom's foundational research contributions included identifying a new method of cross-flow turbine control, demonstrating the influence that turbine geometry could have on performance (e.g., blade static pitch and support strut selection), and identifying the benefits of coordinated control for pairs of turbines in close proximity. Since its founding, XFlow Energy has attracted federal and private funding to develop robust, innovative, and efficient vertical-axis wind turbines and provides technical consulting services in small-scale wind energy technology design and project development.

XFLOWENERGY

In 2016 APL-UW participated in **Joint Industry Projects** (JIPs) to:

- Advance the technological readiness of three, specific wave energy concepts
- Develop related foundational knowledge that would benefit a broader range of technologies
- Engage students, staff, and faculty affiliated with a UARC in real-world, impactful projects
- Strengthen ties between the UARC and industry

Based on responses to a Request for Information, three projects were selected.

The first project, in collaboration with **CalWave**, involved studying the hydrodynamics of heave plates. Most wave energy converter designs need to react against another body to harness wave energy. In shallow water, this reaction force can be generated by the seabed. In deeper water a heave plate located below the wave energy converter may be used to generate this reaction force. While heave plates often have appreciable mass, they generate even greater forces when they move. This added mass associated with the forces is required to displace water during the plate's motion.

miniWEC tests in Lake Washington in support of CalWave and Oscilla Power JIPs. The surface expression consists of a float with the power take-off and control system mounted to the top and a heave plate suspended below. Deployed from R/V *Jack Robertson*, the vessel was also used to produce waves that were characterized by an array of SWIFT buoys.

At the time of the JIP, there was limited understanding of how added mass or damping affected wave energy converter dynamics and how they were impacted by plate shape and flexibility. APL-UW research staff collaborated with engineers at CalWave and a UW Department of Mechanical Engineering student to characterize heave plate forces using a dockside oscillator that emulated the motion of a heave plate connected to a wave energy converter. The research results helped to inform CalWave internal designs and led to a doctoral thesis on the topic.

The second project, in collaboration with **Oscilla Power**, investigated systems-level control and hydrodynamics of a point-absorbing wave converter. Oscilla Power engineers worked with a Department of Mechanical Engineering student to understand the strengths and weaknesses of two software packages to simulate wave energy converters, develop control strategies, and test them in the field using the miniWEC (pp. 10-11). This experience motivated another industry collaboration — the WEC-UUV project (pp. 16-17).

The third project, led by **Siemens**, involved simulation of the pneumatic power take-off unit in an oscillating water column, with the objective of smoothing power output. This supported the development of the utility-scale air turbine used in the **Ocean Energy** 35 wave energy converter, which is planned for deployment at the U.S. Navy's Wave Energy Test Site in 2023.

Overall, the JIPs succeeded in their objectives and motivated a new round of JIPs in 2022. Based on the results of a similar RFI, APL-UW will be collaborating with **CalWave** and **Ocean Motion Technologies**. In both cases the JIPs will advance the technology readiness level of small-scale WEC concepts while generating foundational knowledge relevant to the broader wave energy community.

CalWave — https://calwave.energy/
Ocean Energy — https://oceanenergy.ie
Ocean Motion Technologies — https://www.oceanmotion.tech
Oscilla Power — https://www.oscillapower.com

PUBLICATIONS & PRESENTATIONS

As of March 2023, UW researchers have published 29 peer-reviewed manuscripts in the scientific and technical literature, 21 papers in conference proceedings, made 66 conference presentations, and completed 11 dissertations or theses based on work supported by NAVSEA task orders (p. 2). Products in all of these categories are in the pipeline.

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FUTURE DIRECTIONS

Composing this report has been challenging because it has been a living document — that is, there has always been another major achievement on the horizon that deserved inclusion. Ongoing Navy-sponsored tasks at the Laboratory and University continue to support a range of research and development activities — power generation from marine energy resources, storage and distribution systems for at-sea power, and designs for anticipated loads.

In the field

In the near future we have planned field deployments of marine energy converters including the CPower TigerRAY in Puget Sound and the Turbine-Lander in Sequim Bay, WA, as well as deployments of the Seafloor Power Vault and Oregon State University's Ocean Sentinel (PacWave, OR). Leveraging support from the Department of Energy, UW researchers will also perform environmental monitoring of WECs deployed at the Navy's Wave Energy Test Site (Kaneohe Bay, HI) and multiple turbine deployments in Alaska and Maine. We anticipate new opportunities to develop and deploy marine energy converters and associated technologies to support the Navy's broader objectives of harnessing power at sea.

In the lab

Advances in the field continue to expose unanswered questions related to marine energy converter operations and design that can be addressed with University-based resources. Among other topics, researchers at UW will continue to perform laboratory experiments to increase our understanding of hydrodynamics and related forces that have an important role in device optimization and mechanical design for survivability and operations in extreme marine environments.

Feasibility studies

In parallel to field and laboratory efforts, our teams are focusing on numerical modeling to better understand and predict device performance, using real-world data for validation. For an ocean currents study, we are leveraging existing numerical models to predict global energy resources to inform where current energy converters could be deployed in the future. We are also studying the integration of multiple energy sources at sea (e.g., solar, wind, waves, currents, etc.) and how they can be combined to generate meaningful amounts of power, coupled with adequate storage, to support marine energy systems with higher levels of reliability and in a smaller footprint than is possible with a single energy source.

Collaboration

With Navy support, the Laboratory and University have developed strong relationships with academic researchers at Oregon State University and the University of Hawai'i. We anticipate high levels of ongoing collaboration, leveraging our respective strengths, to address topics of interest to the Navy. We have also established a new round of Joint Industry Projects to advance small-scale wave energy converter prototypes targeting power generation levels necessary for applications like remote sensing and vehicle recharge. In the coming years, we anticipate opportunities to support the transition of similar technologies, including those developed by commercial entities, from lab experiments to field deployments.

Continuing U.S. Navy support for the marine energy research and development community at APL-UW and the University of Washington ensures our role as a leading center in the field. Now and into the future we will execute research and development tasks that benefit the Navy and have broader impacts to the marine energy community — including the education of students and development of professional engineers and technicians.

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