Marine Energy Converter Modeling for Navy Applications

Final Report
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Introduction

Marine and hydrokinetic (MHK) resources have the potential to supply significant power and long-term advantage to the US Navy. Reliable and cost-effective energy conversion technology can provide numerous benefits to both naval facilities and expeditionary deployments. To fully realize these benefits, research, verification, system integration, and technology development are critical.

Researchers at the University of Washington have developed a suite of MHK energy conversion technologies for harvesting tidal energy across a range of architectures (e.g. axial flow, cross-flow), physical scales, rated speeds, and capacities, some which have been tested and deployed at laboratory and field scale, and others that are currently in pre-validation stages of development. Those used in this study are presented in Table 1.

For field deployment of the above or similar technologies, however, proper siting is essential to achieve the expected performance of the device. As the mechanical power of the current varies with the cube of tidal velocities, variations in tidal strength across a channel and across the ebb and flood cycle have significant impacts on the instantaneous and averaged power generated by a device.

Beyond power generation, there are a myriad of parameters affecting the success of failure of an expeditionary deployment of an energy conversion devices that those deploying the device must weigh against the overall power performance of the device, when choosing a deployment location. While there are a variety of performance and micrositing resources available[1] in various stages of development, none take into account expeditionary-specific constraints and requirements.

Objectives

The aim of this work is to develop models of the above prototype systems to serve as a design and decision-making tool to support future MHK projects and/or potential use of these technologies in expeditionary applications.

The modeling required is on two levels. First, numerical simulation of these devices is necessary to estimate their location- and time-specific performance as a function of measured, estimated, or forecast environmental conditions (e.g. MHK resources levels). Second, for this information to be useful in in support of decision-making for expeditionary applications, a micro-siting and optimization toolbox architecture and graphical user interface (GUI) is required.

[1] **Exceedance, Ltd. *Finance***: resource-to-final-outcome techno-economic modeling
DNV-GL *Tidal Farmer*: site-specific, resource-to-annual-energy-yield modeling
DTOcean Plus: open-source, site-specific, resource-to-annual-energy-yield modeling
US Dept. of Energy National Renewable Energy Laboratory *MHK Atlas*: open-source theoretically-available-resource modeling

Major Goals

For the first modeling effort – numerical simulation of the tidal devices – the goal is to develop low-computational cost methods of estimating the performance of characterized devices operating in a tidal resource. For this work, we defined our performance parameters of interest through work with Jennifer Ayers, Ph.D. from the Naval Information Warfare Systems Command (NIWC, formerly the SPAWAR System Center Pacific), and then developed independent models for each of these parameters that could subsequently be used in a broader optimization approach.

Courtesy of Zhaoqing Yang of the Pacific Northwest National Laboratories PNNL, we received access to PNNL's Salish Sea model, featuring high-resolution mapping of the tidal velocities in Sequim Bay, and specifically in and around the tidal channel immediately in front of PNNL's Marine Science Laboratories, where future deployments of Device 1 (see Table 1 and Figure 1) are planned for late 2020 or early 2021. The goal is to leverage the data contained in these measurement-validated models to provide realistic spatially- and temporally-varying tidal velocities, bottom bathymetries, and varying water depths to our tidal turbine numerical simulations.

Table 1. Modeled University of Washington Cross- and Axial-flow Tidal Current Marine Energy Convertors

Device	Area	Base height	Cut-in Speed	Cut-out speed	Rated Speed	Coeff. of Power
1	**1 m^2**	**1.5 m**	**0.75 m/s**	**-**	**2.5 m/s**	**0.85**
2	**0.3 m^2**	**1 m**	**1.00 m/s**	**-**	**3 m/s**	**0.85**
3	**0.8 m^2**	**1 m**	**1.5 m/s**	**-**	**10 m/s**	**0.85**

Figure 1. Renderings of, from left to right, Devices 1, 2, and 3, with the physical and performance properties listed in Table 1. Devices 1 and 2 are a cross-flow turbine and a cross-flow turbine array, respectively, while Device 3 is a axial-flow turbine.

For the latter objective, our main goals were to integrate the individual device numerical simulations into a toolbox capable of recommending a device and siting location, as well as providing realistic estimations of performance in a user-friendly package. The toolbox would ideally be a standalone application that could be utilized by a user naïve to the specifics of marine energy, allowing the user to input specific mission constraints and goals into the graphical user interface, and receive multiple recommendations from the software. All scripting was done in MATLAB.

This application is meant to draw from existing data libraries of measured, modeled, or forecast geospatial met-ocean resource and bathymetric data, a catalog of MEC characteristics, and the user defined mission parameters to run the individual device numerical simulations in a broader optimization routine.

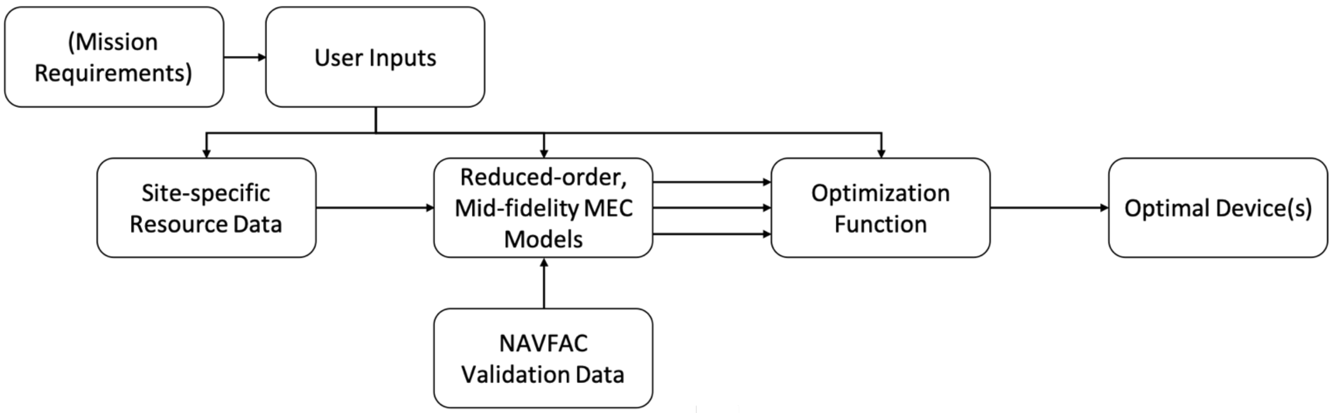

Figure 2. Overview of data flow in the proposed MEC Modeling Toolbox architecture

Our overarching goal was to exercise our resulting product in micro-siting the UW-Applied Physics Laboratory tidal turbine array for the Naval Facilities Engineering Command-sponsored deployment of Device 1 at PNNL's Marine Science Laboratory site in the coming months; and to validate it modeled performance against that of the deployed turbine.

Accomplishments

Overall, we accomplished our major goals, including our overarching goal of a proof-of-concept, standalone application capable of micro-siting the NAVFAC turbine deployment at PNNL's Sequim Bay site. We await the turbine deployment (scheduled for later this year) to evaluate the performance MEC Modeling Toolbox performance estimates.

Identifying the mission requirement space

NIWC staff provided guidance in selecting parameters likely to be relevant to expeditionary deployments of MECs. Table 2 presents the background variables and modeled parameters considered in generating the numerical simulations of device performance for our first objective and major goal; those variables and parameters that were chosen for incorporation into our model are shown in bold.

Table 2. Background Variables and Modeled Parameters for this study.

Independent Variables	User-definable Variables	Modeled Mission Parameters
• temperature • dissolved oxygen • salinity • significant wave height[2] • peak wave period[3] • **current velocity** • **bathymetry** • visibility / water clarity • **julian date** • **device power** • **device capital expenditure** • **device size and mass** • **device acoustic source level**	• **latitude & longitude** • **device depth** • **mission duration** • power transmission distance • deployability • **detectability** • intermittency • maintenance frequency • vulnerability • environmental sensitivity	• **power** • **cost** • **detectability** • reliability • survivability • biofouling • corrosion

The above bolded independent and user-defined variables and modeled mission parameters were chosen as the greatest drivers of device selection and micro-siting based on APL's ongoing turbine array development and deployment work and NIWC's input on mission constraints. Each of the variables and parameters was subsequently built into the final version of the MEC Modeling Toolbox.

Acquiring and incorporating underlying met-ocean and MEC characteristic data

After identifying the variables and parameters for the toolbox, the next major accomplishment of this work was integrating the underpinning oceanographic models and turbine characteristics into a numerical simulation tool capable of estimating turbine performance at a given latitude, longitude, depth, and over a specific window of time. This work built upon PNNL's Salish Sea model and specifically upon a higher spatially- and temporally-resolved map of Sequim Bay developed by Zhaoqing Yang (see Figure 3). The Sequim Bay model is built in the Finite-Volume, primitive equation Community Ocean Model (FVCOM) environment.

Major challenges in the integration of this baseline model came in the structure of the data, which required conversion to cartesian coordinates and referencing to the local bathymetry, intelligent interpolation, and validation against existing acoustic doppler current profiler surveys taken in preparation of upcoming DOE-[4] and NAVFAC-funded research.

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[2] Significant wave height was considered in an add-on numerical simulation for wave energy converters not currently included in the MEC Modeling Toolbox

[3] Peak wave period was considered in an add-on numerical simulation for wave energy converters not currently included in the MEC Modeling Toolbox

[4] Harding, S.F., Hall, K.D., Vavrinec, J., Harker-Klimes, G.E.L., Richmond, M.C., (2016). "Field Characterization of Triton Tidal Site: Vessel-Mounted ADCP Survey of Sequim Bay Inlet" *Report*. Pacific Northwest National Laboratories.

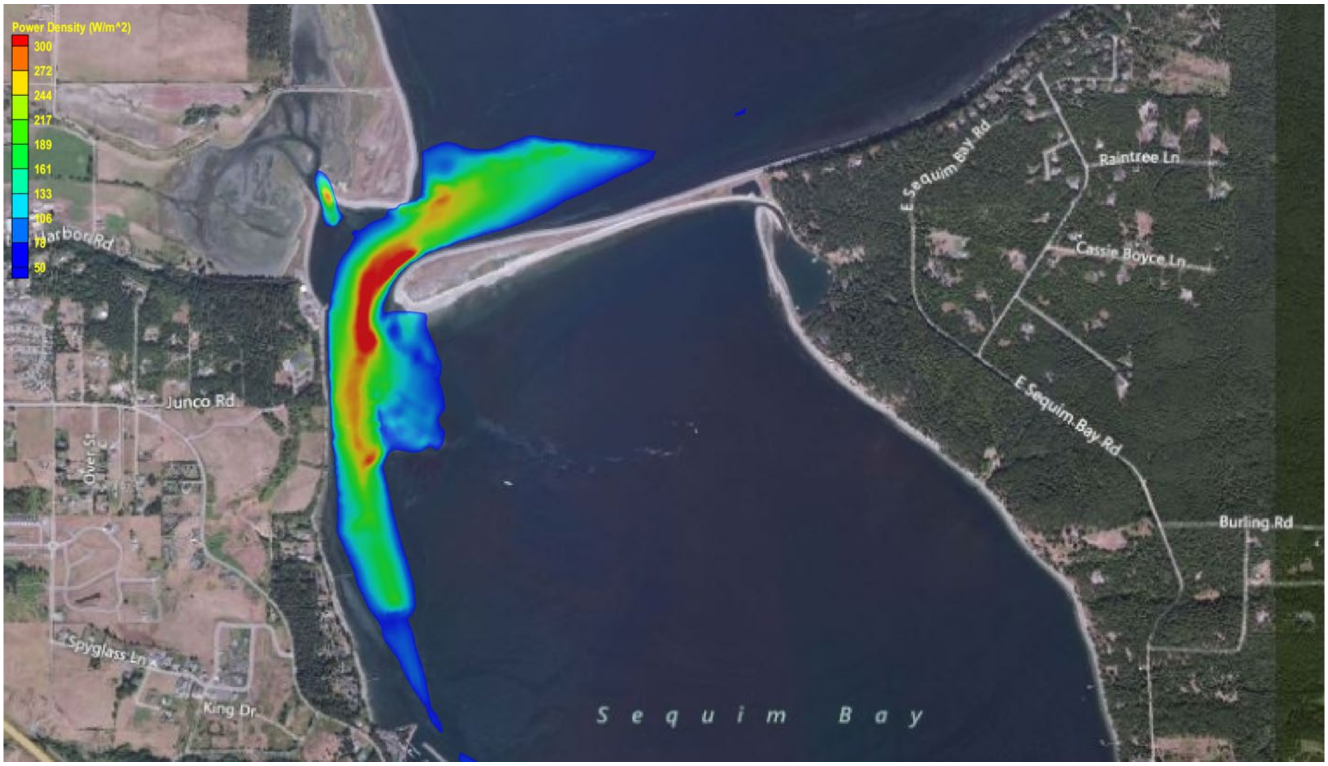

Figure 3. Time- and depth-averaged modeled tidal kinetic power at Sequim Bay, WA (courtesy of Pacific Northwest National Laboratories)

The catalog of turbine characteristics were taken from archival data of turbine performance, cost, and noise levels from prior and ongoing UW work; often extrapolated from research conducted in a one-quarter- to one-third-scale flume. While the work formed a strong basis for these parameters, the field-scale (approximately $1m^2$) turbine characterization efforts expected to be complete prior to this study were significantly delayed, and are only now beginning in mid-2020. As the specific values are programmable in firmware of the numerical simulations and the broader toolbox architecture, this is easily updated when more accurate values are available. Regardless, a catalog describing the relevant parameters of both cross-flow and axial-flow turbines was developed and propagated through the numerical simulations and toolbox, and verified to generate realistic estimates of power, cost and acoustic detectability range.

Developing mission parameter models

Three primary, low-computational-cost numerical simulations, or modules, that convert the independent (met-oc model or device characterstic) variables and user-defined variables (mission requirements) into modeled, optimizable parameters were built under this work.

The first and simplest numerical model leveraged pre-existing work done by the National Renewable Energy Laboratory in establishing metrics for estimating the cost of Marine Energy Converters (in that case wave energy converters)[5]. Fundamentally, this method takes a representative

[5] U.S. Department of Energy (2016) "How does the Wave Energy Prize Calculate ACE?" https://waveenergyprize.wordpress.com/2016/08/18/how-does-the-wave-energy-prize-calculate-ace/, last accessed (8/2017) Andres, A., Maillet, J., Todalshaug, J.H., Moller, P., Bould, D., and Jeffrey, H. (2016) "Techno-Economic Related Metrics for a Wave Energy Converters Feasibility Assessment", *Sustainability*, 8(11), 1109

geometry of the device, assumes a structural member thickness (which can be thought of as a skin-thickness for more complicated shapes), and scales by a cost per volume of material. Written out, the characteristic Capital Expenditure, *CCE*, is:

$$CCE = SA \times \delta \times \rho \times \mathrm{C}$$

where *SA* is the surface area of the device, δ is the representative structural thickness, ρ is the density of the structural material, and *C* is the cost of manufactured material per unit mass. While crude and potentially inaccurate, this estimate is consistent and provides a robust *comparative* measure between devices, which is the relevant criterion in the later optimization step within the toolbox.

The second, more involved numerical model is the acoustic detectability distance of the device, taken to be the radius at which the signal to noise ratio falls below a critical threshold (e.g. 0.001). This model leverages the sonar equation:

$$SNR = SL - TL - NL$$

where *SNR* refers to the signal to noise ratio, *SL* is the source level of the device, *TL* is the frequency-dependent transmission losses, and *NL* is the site-specific ambient noise level[6]. The initial model assumes a spherical geometric spreading with no reflection, refraction or diffraction, but the model could be expanded in future efforts to include more complicated spreading of acoustic energy (e.g. wave guides). As currently configured, the model provides the radial distance from the device where the signal to noise ratio falls beneath the desired threshold (see Figure 4). Source Level as assumed to increase with current rotation speed, and we took a measured, representative ambient noise level for the local area[7].

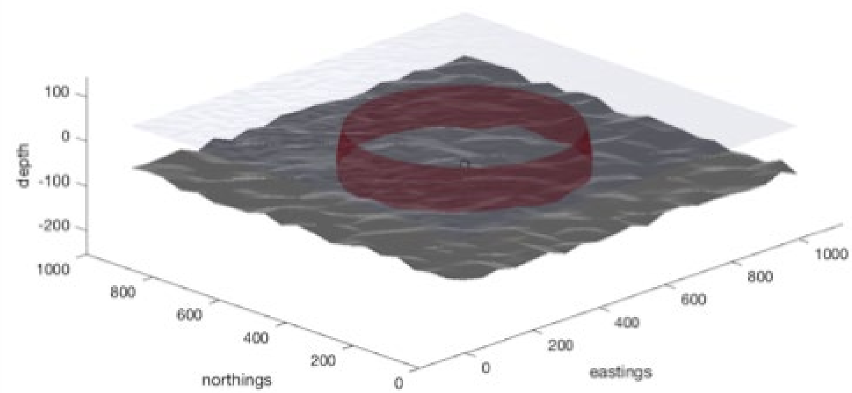

Figure 4. Illustration of the critical radius of acoustic detectability in shallow water, assuming purely spherical spreading of acoustic emissions from a bottom mounted device.

[6] Fisher, F.H. & Simmons, V.P. (1977), "Sound Absorption in seawater", Journal of the Acoustical Society of America, 62, 558-564
[7] Bassett, C., Polagye, B. Holt, M. and Thomson, J. (2012), "A vessel noise budget for Admiralty Inlet, Puget Sound, Washington (USA)" Journal of the Acoustical Society of America, 132 (6), 3706-3719

The third and most intricate numerical simulation – and where the bulk of this effort fell – was the development of a low-computational-cost estimator of an MEC device's power output. This numerical simulation took in information from the met-ocean models or forecasts, the device characteristic catalog, and the user-defined inputs, and output peak and average power for given locations, depths, and durations. Fundamentally, this leveraged the coefficient of performance, C_P:

$$C_P = \frac{P}{0.5\,\rho A U^3}$$

Where *P* is the power produced by the turbine, *ρ* is the density of the water, *A* is the rotor-swept cross-sectional area of the current, and *U* is the current velocity and a function of *x, y, z,* and *t*. This coefficient of performance varies with tip-speed ratio, that is the ratio of the rotation compared to the background velocity of the water.

As the tidal current increases from a slack tide, the turbine generates no power until a cut-in speed is reached, at which point the low power increases exponentially as a function of the background flow speed (and direction), tip-speed ratio, and the coefficient of performance. This increase continues until the turbine reaches its rated power, at which point the turbine engages power-shedding strategies (most often operating in an off-peak tip-speed ratio to reduce power), and power production becomes constant at rated power as the current speed increases. Finally, if a high enough current speed is reached, the turbine will attempt to stop operating and ceases to produce power (see Figure 5). Tidal flow reverses multiple times each day, passing through the cut-in speed and – presuming the appropriate turbine is specified for the location – increasing up to the rated speed and beyond. The power produced, therefore, is not as simple single-value C_P calculation, particularly as it is reproduced across multiple devices, locations, and times in the optimization engine of the Toolbox.

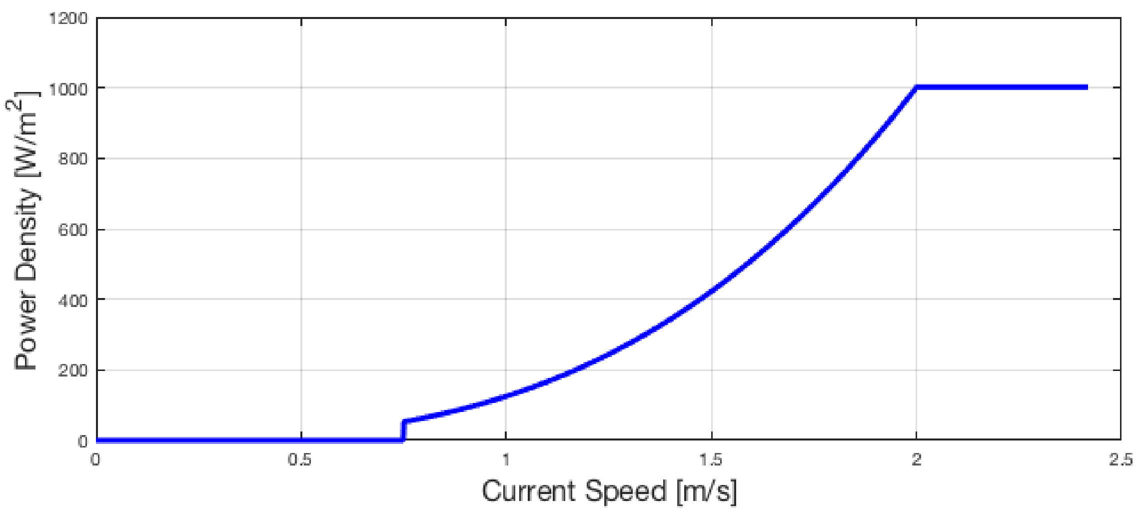

Figure 5. Power per unit area as a function of tidal current speed, showing device cut-in, ramp-up, and rated power per unit of rotor-swept area.

The turbine module was developed extensively by the UW mechanical engineering doctoral student, Trent Dillon, over the course of this project, and became the foundation for his subsequent dissertation research in MEC modeling and optimization. Results from this module were verified against reasonable values for power output extrapolated from flume tests of reduced-scale turbines, both cross- and axial-flow, over the range of current velocities and tip-speed ratios.

Numerical simulation integration & data flow

The above numerical simulations of turbine performance, cost, and acoustic emission modules were constructed so as to easily pull required data from the underpinning met-ocean simulations, MEC device characteristic catalog, and user-defined variables. These modules were then integrated into an overarching software architecture that, at its core, efficiently ran multiple iterations of the simulation modules at each possible physical location over the specified time window and for each potential device in the catalog, before running an optimization to determine the best locations and devices for deployment.

The software architecture is represented in the diagram in Figure 6. For the sake of processing speed, the met-ocean and device data sets are pre-processed upon program launch, yielding a set of proxies for power, cost, and acoustic emission at each spatial grid point and time. When the user-specifies values for location, time window, depth, power, and cost mission requirements, the software reduces these pre-processed proxies to a smaller data set which can then be optimized at a lower computational cost.

This reduced set of proxy data is then optimized per an objective function which penalizes greater critical acoustic detectability range of the device, higher costs, and *lower* power production. The penalty in each of the three dimensions are calculated for each device, at each model locus of the appropriate height from the sea-floor (determined by the device characteristics catalog). From there, the 3-dimensional objective space is populated with the penalty values within the user-specified constraint space (of depth, power, cost, and acoustic threshold distance).

The software's multi-objective optimization engine seeks to minimize the penalty by searching for Pareto optimality within the objective space. The algorithm identifies a Pareto frontier composed of points that are *non-dominated*, i.e. where the constituent device-location combinations represent the lowest penalty along one or more of the axes and no other device-location point *dominates* it. In other words, a device-location combination is in the Pareto set if another device-location combination can not be found where the penalty along one dimension (e.g. acoustic emission) doesn't incur greater penalty in the remaining dimensions (e.g. power, and financial cost). A graphical representation of the objective space is shown in Figure 7.

First, second, and third rank Pareto-optimal solutions are calculated for each user-specified input at the GUI. These ranked Pareto sets of device-location solutions that satisfies the user-defined constraints is the solution set that this then passed back to the user, via the graphical user interface.

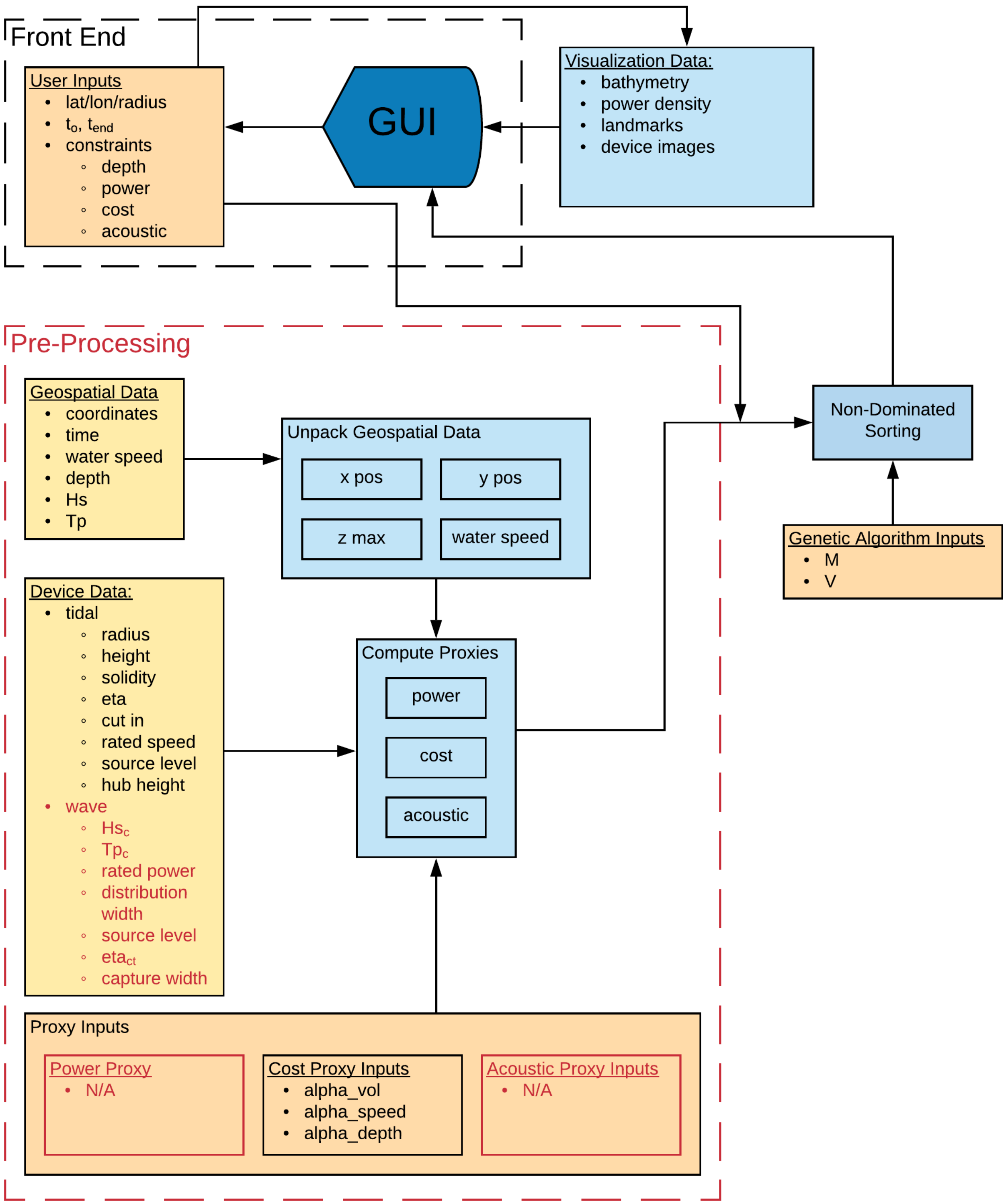

Figure 6. Software system architecture and data flow.

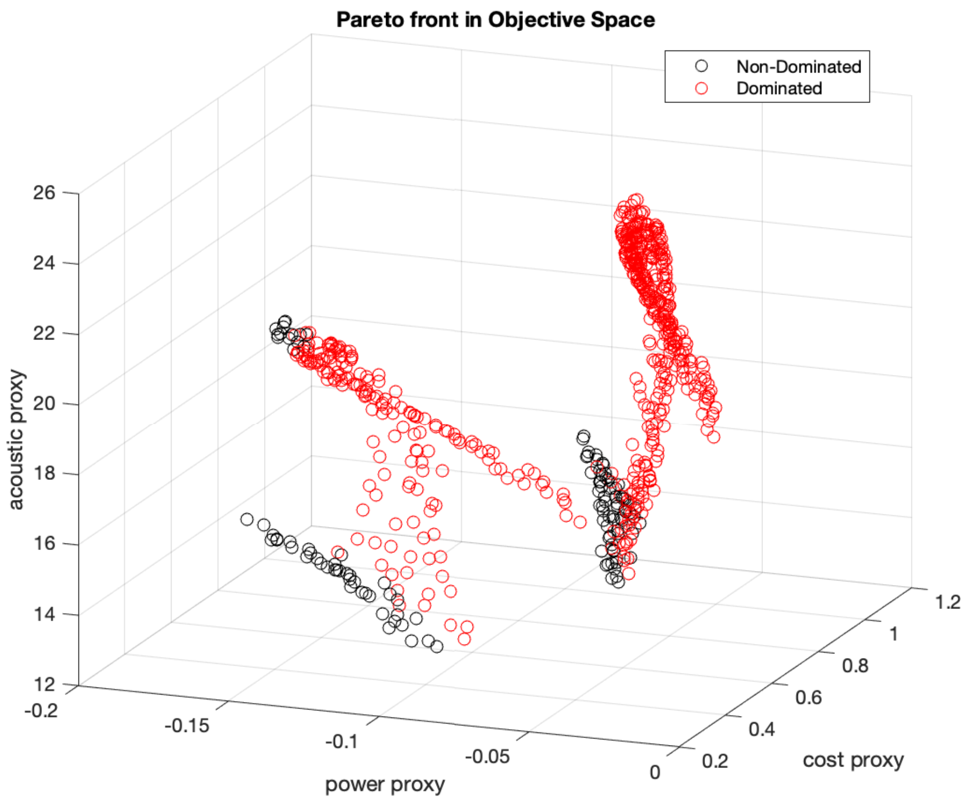

Figure 7. Objective space for Pareto Efficiency multi-objective optimization. Black circles show the non-dominated Pareto frontier of device-location combination solutions.

Graphical User Interface

A pivotal component of this software package is the graphical user interface, which was developed to allow a naïve user, one with no significant expertise in marine energy converters, to utilize the software to select the best device to deploy in a location and time window and within to mission requirements and constraints.

Working with MATLAB's GUI design tool, we produced a map-based GUI allowing the user to choose deployment location, spatial search radius, time window, and the relative importance of low cost versus higher power performance. The user clicks on the map to choose the center of the search location, and the defines a radius over which to optimize device-location pairs. The user may also specify a new time window with sliders, and the relative weighting of the various objectives. Moving any slider on the GUI is accompanied by a processing pause, while the 'map updated' indicators switch to red until the map is recalculated and the new results are displayed.

The results are displayed overlain on a power "heatmap" showing the interpolated time- and depth-averaged power density of the tidal current over the specified time window at each latitude and longitude. For each gridpoint of the underlying FVCOM met-ocean resource model where there is a Pareto-optimal device-location pair, the graphical output shows the corresponding green geometric shape at that location; nothing but the gridpoint is shown for locations without a Pareto-optimal device-location pair. See Figure 8 for a screenshot of the GUI with actual data.

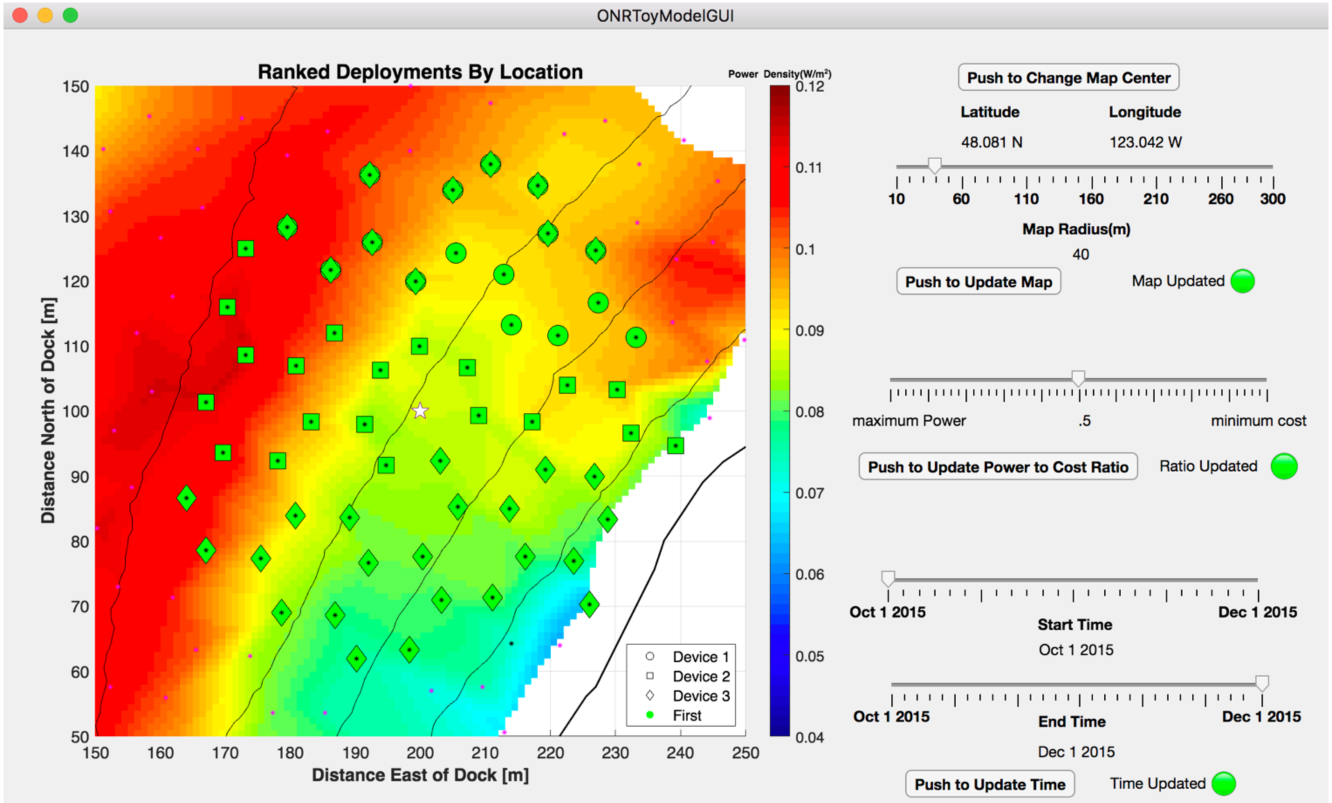

Figure 8. Graphical User Interface showing Pareto-optimal device-location pairs of the first order at Sequim Bay, WA.

The GUI is intentionally constructed such that a user with no previous knowledge of marine energy can select the relative value of parameters (in the above iteration of the GUI, power vs. cost), as well as the location and duration of the mission, and generate relevant, useful results. Previous iterations of this software included user input fields for wattage, dollar, and acoustic radius lengths in addition to the location and duration; however, with the limited number of characterized devices available to be cataloged, this GUI form was chosen to more directly showcase the concept.

A software user may access this program as a MATLAB Standalone Application, or within the MATLAB environment, and runtimes for the example shown, including startup and preprocessing of proxy data, were on the order of minutes to tens of minutes on a typical PC laptop. The script and App were also tested and shown to function on Mac OS with similar runtimes. Preprocessing and analysis, however, will scale with the underlying datasets, with larger met-ocean datasets requiring exponentially more time, while larger device catalog runtime should scale linearly.

Verification & Validation

Results generated with the Toolbox were internally verified at various stages of the project. Individual modules for acoustics, cost, and power performance were each measured against hand calculations during their individual development, and found to be accurate. As complexity increased, the cost function was verified to be properly penalizing decreased acoustic critical radius, increased cost, and decreased power performance. In the objective space, the non-dominant sort methodology to identify device-location pairs on the front was also visually verified (e.g. Figure 7). Finally, the results plotted to the GUI were verified against independent runs of the verified modules, optimization function, non-dominant sort, and background met-ocean model.

Due to delays in complementary activities, there were no opportunities to validate the device selection or micrositing – and ensuing acoustic, cost, and power performance - against an actual physical deployment of the device. Plans for a "Device 1" deployment in Sequim Bay, WA under an ongoing NAVFAC project were repeatedly delayed, due primarily to permitting challenges, and are currently scheduled for summer 2020, though that is now likely delayed as well, due to the COVID-19 pandemic. Preliminary work for the siting of that deployment, undertaken with a small, shipboard ADCP, showed highly congruent results with the MEC Modeling Toolbox predictions.

Outcomes

Training

Under this award, funding was provided to doctoral student, Trent Dillon, in the Mechanical Engineering Department at the University of Washington, outside of the term provided by his National Science Foundation Graduate Research Fellowship Program funding. Trent worked closely with the P''s and other research scientists involved with this program on each of the steps of this effort, and – now in his final year of research in his doctoral program – reached a point where he is contributing more as a colleague than a student.

This work inspired a number of complementary efforts by Trent, including the foundation of his Ph.D. research topic, on the site-specific selection and optimization of at-sea power generation, storage, and instrumentation load. Work on the tidal turbine power generation module spawned an interest in repeating the approach for a less deterministic system, wave energy; and the subsequent development of a promising markov decision process optimization of wave energy MEC-instrumentation system operation/load management.

Mr. Dillon was also integrally involved in the site selection efforts for the complementary NAVFAC "Device 1" deployment, where he broadened the scope of the multi-objective optimization approach (e.g. to include device overturn potential, potential vessel interference, etc.). His results were highly influential in the final selection of the device, and were influenced by methods employed in this research.

Dissemination

This work has been disseminated primarily through oral and poster presentations, and associated conference articles. At the close of this period of performance, the work had been accepted for presentation at the 2020 International Conference on Ocean Energy (ICOE) in Washington DC. However, this conference has been cancelled due to the ongoing COVID-19 pandemic.

Initial results were presented at ICOE 2018 in Cork, Ireland by oral presentation, where they were well received. An associated conference proceedings was submitted and accepted.

These results were also presented by poster to an early-career audience at the annual meeting of the International Network of Offshore Renewable Energy (INORE), in 2017.

The offshoot project of micro-siting the Sequim Bay, WA "Device 1" deployment was presented to the Marine Energy Technology Symposium as a part of Hydropower Week in Washington, DC in 2018.

Honors

None.

Technology Transfer

None.

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14. ABSTRACT
Our overarching goal was to exercise our resulting product in micro-siting the UW-Applied Physics Laboratory tidal turbine array for the Naval Facilities Engineering Command-sponsored deployment of Device 1 at PNNL's Marine Science Laboratory site in the coming months; and to validate it modeled performance against that of the deployed turbine. Overall, we accomplished our major goals, including our overarching goal of a proof-of-concept, standalone application capable of micro-siting the NAVFAC turbine deployment at PNNL's Sequim Bay site. We await the turbine deployment (scheduled for later this year) to evaluate the performance MEC Modeling Toolbox performance estimates. Major challenges in the integration of this baseline model came in the structure of the data, which required conversion to cartesian coordinates and referencing to the local bathymetry, intelligent interpolation, and validation against existing acoustic doppler current profiler surveys taken in preparation of upcoming DOE and NAVFAC-funded research.

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