Graduate Research Plan Statement

Hypothesis: Ocean wave energy has vast potential as a renewable power source, but traditional sequential design methods perpetuate prohibitively high device costs. **Applying systems optimization techniques to wave energy would unlock new architectures that are cost-competitive at utility scale.**

Introduction: Climate change is the most critical problem facing humanity. It threatens warming, flooding, erosion, and storms that damage infrastructure, agriculture, health, and biodiversity. The fatal potential for 4ºC of warming can be limited to 1.4ºC if complete decarbonization occurs by 2055 [1]. The electricity sector contributes 40% of global CO_2 emissions, representing perhaps the largest challenge and opportunity for decarbonization [2]. Existing renewables have limitations: wind and solar are intermittent and unpredictable; hydropower and geothermal have few suitable sites. To reach 100% clean electricity, we must supplement these sources by developing diverse renewables to technical and economic maturity. Ocean wave energy is uniquely attractive due to its predictability, geographic abundance, and continuous availability [3]. Despite an ability to fulfill 34% of US electricity demand [4], wave energy technology's high cost, long design cycles, and risk-intensive investment have prevented full-scale deployment [3].

The wave energy converter (WEC) industry has so far followed a trajectory similar to aerospace, focusing on technical risk reduction with an expectation that costs will fall after the technology matures. However, recent analysis indicates that this path is infeasible, and success hinges on a reinvention of the typical design cycle to emphasize early cost and performance innovation before deploying expensive prototypes [5]. **Multidisciplinary Design Optimization (MDO) and Control Co-Design (CCD) techniques can provide the design paradigm shift that is required for dramatic cost reduction.**

MDO and CCD are emerging techniques that depart from the standard sequential design process by considering subsystem interactions early on. MDO is an optimization framework for interdisciplinary design problems. MDO has been used successfully in the automotive, energy, and aerospace sectors but never attempted for wave energy due to novelty and computational costs [6]. CCD, the use of control principles to inspire device design, has never been applied to a utility-scale WEC for similar reasons. CCD offers significant benefits: in offshore wind turbines, CCD decreased structural loading by 99% [7], and one estimate predicts 30% cost reduction potential for wave energy [8]. Overall, MDO and CCD are promising methods to advance wave energy design towards full decarbonization of the electricity sector.

Research Plan: This project will be completed over the course of my PhD studies at Cornell University in the Symbiotic Engineering Analysis (SEA) Lab, led by Professor Maha Haji.

Objective 1: Develop a novel WEC design framework using principles of MDO and CCD. I will create a multidisciplinary model of WEC dynamics and performance. As shown in Fig. 1, the model will bridge previously disparate simulations in controls, structures, powertrain, and hydrodynamics, which are recognized as the four most impactful subsystems to drive down WEC costs [9]. I will prioritize appropriate model fidelity, simplifying wherever feasible while still capturing important subsystem interactions. One key tradeoff is the decision to model in the stochastic, frequency, or time domain. Degrees of freedom will be selected strategically, balancing computational tractability against flexibility to describe diverse architectures. Objective 1 is attained when a design optimization process can be clearly articulated and validation efforts show that the model can correctly predict performance of existing WECs. This framework forms the foundation for the second research stage.

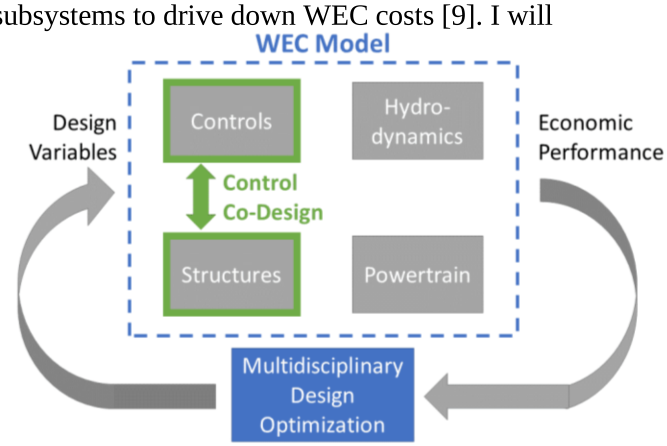

Figure 1: The proposed design process integrates Multidisciplinary Design Optimization (MDO) and Control Co-Design (CCD).

Objective 2: Utilize the design framework to obtain a novel WEC architecture that is cost-competitive at utility-scale. The MDO-CCD model and process developed in Objective 1 will be implemented and iterated upon, focusing on interactions between device controls and structures. Initially, optimization will identify the best combination of existing configurations; ultimately, model degrees of freedom will be extended, allowing optimization to yield new architectures altogether. Sensitivities will quantify impacts to inform further innovation. Objective 2 is complete when a WEC design with levelized energy cost below $0.30/kWh is found, representing a 75% cost reduction from current technology [10].

Objective 3: Validate key features of the optimal design through wave tank testing. The final stage of research involves the detail-design of a scaled prototype of the optimal solution, followed by the manufacturing, testing, and data analysis of the prototype. The testing investigates real-time control implementation, validates model robustness, and provides a practical industry-relevant realization of the new design process and design. Cornell University is equipped with the facilities to enable this testing through the DeFrees Hydraulics Lab wave tank, and collaborations with nearby institutions including the University of New Hampshire or the University of Maine could be leveraged for larger wave tank access. Objective 3 is complete when any major differences between model and test are identified and explained.

Intellectual Merit: Wave energy is an under-utilized and under-researched renewable source with great potential. Multidisciplinary integration is expected to be a key enabler of future cost-competitive wave energy. The proposed work will be the first to apply MDO and CCD techniques to a utility-scale wave energy converter, potentially unlocking radical cost savings. My design process will be the first to unify disparate WEC domains; my optimization will provide new insights to advance the field toward design convergence; and my test data will confirm understanding and applicability of these novel contributions. My undergraduate background provides relevant technical depth in mechanical design, power electronics, hydrodynamics, and controls, and above all I have the systems mindset to effectively unify these fields. This experience, coupled with the SEA Lab's expertise exploiting synergies in marine technologies, uniquely qualifies me to succeed at the proposed research.

Broader Impacts: Wave energy has the potential to meet 34% of national electricity demand [4]. My research will enable cost-competitive wave energy, adding to the renewables mix to combat climate change. The integrated MDO-CCD design process applies widely to any system with multidisciplinary interactions and embedded dynamic controllers. Thus, the proposed research advances knowledge in both renewable energy alternatives and systems optimization methods, both of which broadly benefit society.

To circulate my research to the academic community, I will publish in journals such as *Ocean Engineering* and *Renewable Energy* and present at diverse venues such as IEEE OCEANS and CESUN. Leveraging my advisor's connections, I will initiate collaborations with the National Renewable Energy Lab and companies such as CalWave. These partnerships will amplify the impact of my research by ensuring its alignment with current industry goals and its rapid dissemination to others upon completion.

Finally, I will engage in outreach to both the general public and students of all backgrounds. Societal acceptance is key for widespread adoption of wave energy technology, and education about the opportunities and challenges of renewable energy encourages sustainable habits as well as an interest in engineering. My contributions to STEM outreach and curriculum development through SWE, Splash, and GRASSHOPR are detailed in my personal statement. **In sum, my work as an NSF fellow would promote STEM engagement, advance systems design techniques, and enable a carbon-free future.**

References:
[1] "Climate change 2021," IPCC, 2021. **[2]** "Net zero by 2050," IEA, 2021. **[3]** F. Mwasilu and J. Jung, *IET Renewable Power Gener*, 2019. **[4]** L. Kilcher, *et al.*, NREL, TP-5700-78773, 2021. **[5]** D. Bull *et al.*, Sandia, SAND2017-4507, 2017. **[6]** J. Sobieszczanski-Sobieski and R. Haftka, *Struct. Optim.*, 1997. **[7]** X. Du, *et al.*, ASME 2020 Int. Mech. Eng. Congr. and Expo., 2021. **[8]** M. Garcia-Sanz, ARPA-E, 2018. **[9]** D. Bull, *et al.*, Sandia, SAND2013-7204, 2013. **[10]** G. Chang, *et al.*, *Renewable Energy*, 2018.