Adaptive hierarchical model predictive control of wave energy converters (AHMPC)

WES Control Systems Stage 2
Public Report

Dr Guang Li

Queen Mary University of London

This project has been supported by Wave Energy Scotland

1 Project Introduction

The project aims to develop a reliable and efficient control strategy to improve the wave energy converter (WEC) conversion efficiency and survivability over a wide range of sea states. This is to be achieved by integrating some enabling technologies in control and wave prediction into a hierarchical control framework to achieve the salient advantages: maximum energy output subject to constraints, robustness to modelling uncertainties, and survivability in different sea states.

Essentially, we employ a deterministic sea wave prediction (DSWP) technique to predict the incoming waves, and this information is used to predict the sea state and provide this non-causal wave information to the model predictive control (MPC) to improve performance. According to the sea state, a weighting function is tuned for the MPC controller and the WEC model is adaptively updated, so that the optimal performance of the MPC controller can be maintained over a wide range of sea states. To accurately estimate the WEC state for the opitmal state feedback controllers, a robust sliding mode observer (SMO) is adopted, which can handle modelling uncertainties effectively. This framework combines the strengths of MPC, adaptive control, SMO and DSWP technique. Although this control framework is suitable for generic types of WECs, we mainly focus on a typical attenuator type of WEC developed by Mocean Energy Ltd (we will refer to this WEC as Mocean WEC in this report) as a case study. This WEC is a two-float and multi-motion WEC, which has higher energy conversion efficency than a single-motion and single-float WEC, e.g. a point absorber; however, it has more complicated hydrodynamics than a point absorber, which brings much more challenging issues in modelling and control. The techniques developed in this project can be easily extended to other types of WECs, e.g. the point absorber, as demonstrated in our published results in public domain.

In Stage 2, we have further developed the control framework proposed in Stage 1, and validated its efficacy thoroughly by numerical simulations. The simulation results show that the performance can be improved by 10% to 90% in most sea states for the Mocean WEC. We also conducted a co-design exercise, combining the controller design and the power take-off specification, of the Mocean WEC. We demonstrate that the unit cost of the electricity can be reduced by 8% and the annual energy output can be increased by 30% to 40% when our controller is used, compared to the case when no active feedback controller is used and the WEC's damping ratio is well tuned by trial and error.

The team include members with complementary expertise in control, wave prediction and wave device design etc. from Queen Mary University of London (for development of control strategies), University of Exter (for wave prediction, robustness handling, and state estimation) and Mocean Energy Ltd. (for device design and testing).

2 Description of Project Technology

The overarching objective is to develop an adaptive hierarchical model predictive control (AHMPC) framework with self-adaptive tuning mechanism to maintain the high performance of advanced optimal controllers at various sea states so as to improve performance and operation safety of WECs. The proposed control framework has more benefits than the existing WEC control strategies thanks to the enabling technologies recently developed in our recently published works, e.g. [1-7], [9-15], [17]. Compared with MPC or linear optimal control only tuned and based on one fixed WEC model at one particular sea state, the proposed AHMPC can maintain satisfactory performance and robustness when sea state is changed. Moreover, AHMPC explicitly incorporates constraints optimally, whilst the existing adaptive algorithms for WEC control can only achieve a suboptimal solution when the system is subject to constraints. The major advantageous features of this control framework are summarised as follows:

1) **Constraints handling.** A WEC system is normally subject to constraints on power take-off (PTO) actuators and float motions. Effectively coping with these constraints has direct influences on safety and hardware cost. MPC has been proven to be the most efficient control strategy to tackle constrained optimal control problems. This advantageous feature of MPC can be inherited by the proposed AHMPC framework to explicitly incorporate constraints into energy maximisation. We have compared the performance of MPC with our recently developed linear optimal controller (LOC) for WECs. We find that for small wave height, the performance of MPC and LOC are similar; however, the advantage of using MPC becomes more obvious at high sea states when actuator saturation becomes more severe. Our simulation results at Stage 2 show that the constraint handling feature of MPC can improve the energy output with strict satisfactions of the constraints. Since the Mocean WEC PTO cost is proportional to the PTO torque capacity, we have integrated the control framework into the co-design of the Mocean WEC to find the optimal trade-off between the cost of the PTO and the maximum energy conversion efficiency, which shows that the unit cost of energy can be reduced by 8%.

2) **Adaptive tuning mechanism for various sea states.** Since the WEC dynamics can change dramatically across a broad range of sea states, it is essentially important to update the WEC model in real time to handle model dynamics variations. We have used several techniques to tackle this problem. A recently developed effective adaptive parameter estimator (APE) [9-11] is employed and specifically tailored for WEC dynamic parameter estimation problem. Our simulation results show that the dynamic parameters corresponding to the radiation force estimated by the APE technique can converge to the real values within 60 seconds for the Mocean WEC and the convergence time for those of a benchmark point absorber is within 20 seconds. These convergence periods are much shorter than the time needed for the change of sea states. To develop a high fidelity WEC model to represent the WEC dynamics in a wide range of sea conditions can be very challenging and the MPC controller based on an overly-complicated model can cause heavy computational burden for its online implementation. Thus a trade-off between the modeling fidelity and complexity must be found by reducing the order of the model for controller design, which inevitably introduces the “unmodeled dynamics”. Note that the state-space model of the multi-body, multi-motion Mocean WEC has hundreds of states even after model order reduction (See **D01**). To address this problem, we propose the AHMPC framework for WEC systems. On the top layer, a cascaded adaptive parameter estimation mechanism is designed to identify and update the frequency-dependent dynamics so that the WEC model can track the potential variations of the WEC dynamics corresponding to the change of sea states. Then the online updated dynamic model is employed by the bottom layer, where a specially-tailored MPC is designed based on the updated model to maximize the energy output and keep the constraints satisfied for safe operation purpose. In Stage 2, we have fully developed this methodology and tailored it for the Mocean WEC control problem. The efficacy of this control methodology has also been demonstrated by a benchmark point absorber and published in conferences and journals [9-11].

3) **Handling dynamic uncertainties.** To enhance the robustness of the proposed control framework, we employed Sliding Mode Observer (SMO) to online estimate the WEC states and wave excitation force. To demonstrate the efficacy of SMO we have made comparison with the existing Extended Kalman Filter (EKF). Our simulation results on the Mocean WEC show that SMO outperforms the EKF for excitation force estimation by producing significantly less estimation errors while not increasing computational burden. This significant improvement of estimation accuracy can improve the robustness and performance of the proposed AHMPC framework.

4) **Non-causal control with reliable wave prediction information.** WEC control is a non-causal control problem; by “non-causal” we mean the current control decision is not only dependent on the current WEC

state and sea information, but also the future wave information. It has been well recognised that future wave information is needed to achieve an optimal solution for WEC control. The efficient and reliable deterministic sea wave prediction (DSWP) technique can be integrated into the framework to realise the non-causal control. The efficacy of DSWP has been demonstrated in sea wave energy and other marine applications, and validated in real sea trials [17]. Our Stage 2 results show that wave prediction information can play a major role in improving the performance. We compared the performance of non-causal optimal controllers (MPC and linear optimal controller) and their corresponding causal counterparts. We find that the non-causal controllers can improve the energy output from 10% up to 300% in different sea states and testing scenarios for the Mocean WEC. In the meantime, we have also made comparisons using other WECs, e.g. a point absorber, which confirm that the benefits of using the non-causal control are also very significant.

5) **Fast optimisation algorithm.** All of the control algorithms are developed for real-time implementation. Every effort has been made to find a trade-off between computational load and control performance so that the resulting AHMPC framework can be implemented online using the economically viable computational hardware. Specifically, for the derivation of control oriented model for controller design, the model order reduction technique is used to find the balance between the order of the WEC model and the model fidelity. The influence of nonlinear effects are also thoroughly investigated to find the trade-off between the controller design complexities, computational load and control performance. For the controllers, the LOC controller gains can be designed offline, which causes trivial computational load; the MPC controller can be efficiently implemented online by resolving the convex quadratic programming problem using maturely developed optimization methods, e.g. active set method and interior point method; the online parameter estimation technique can be implemented with very small computational load; the state observers based on the sliding mode method and Kalman filter method are designed by avoiding fast poles to reduce computational load.

Besides the above specific advantages, the proposed framework enjoys a salient beneficial feature: the flexibility for modification. The technologies embedded into the framework can be flexibly modified or replaced by other alternative techniques to meet control requirements for different types of WECs. For example, when the constraints become a less important factor to consider for some WEC designs, the constrained optimisation algorithm can be replaced by the recently developed unconstrained linear optimal control (LOC) specifically tailored for wave energy maximisation problem with trivial computational load [3]; when the influence of uncertainties on state estimation diminishes for WEC model with sufficient fidelity, we may use a conventional Kalman filter to simplify the design procedure. This flexibility feature also makes the proposed project very robust with great risk mitigations regarding technology transfer and development. Our stage 2 simulation results show variant comparisons of different control techniques.

All these advantageous features of the proposed control framework can contribute to the improvement of the overall performance of the WECs through improvement of reliability, maintainability, performance, manufacturability, integratability and stability, etc, so that the levelised cost of energy (LCOE) of wave energy can be reduced significantly. This project also benefits from technology transfer from our other ongoing projects funded by EPSRC (“Launch and Recovery at High Sea States”) and the Royal Society Newton Advanced Fellowship and Newton Exchange Programme, etc.

3 Scope of Work

The scope of Stage 2 project mainly involves activities in the following areas:

Area 1: Derivation of the control-oriented models for the Mocean WEC. The state observer and the core controllers, MPC and LOC, embedded in the proposed AHMPC framework need to be designed based on a control-oriented model of a WEC. We call such control designs as model-based control designs, which are contrast to the model-free control design methods, e.g. some PID control methods, and the controls based on a black-box model identification technique. We have successfully derived the state-space model from the hydrodynamic model of the Mocean WEC and further reduced the order of the state-space model to alleviate the computational load of the controller to be designed based on this model. The reduced-order state space model is validated against the original hydrodynamic model of the Mocean WEC quantitatively.

Area 2: Development of the AHMPC and the key enabling technologies. We have developed and validated the efficacy of each proposed technology, their compatibility and performance comparisons of counterpart technologies based on the Mocean WEC. From our numerical simulations, we have confirmed the improvement of performance by integrating wave prediction information into controller design, the importance of explicitly accounting for constraints on PTO limit, the robustness enhancement by sliding mode observer, the benefits of adopting online parameter identification and dynamic model updates. Some simulation results based on a popularly studied point absorber have been published in journals and conferences, see e.g. [4-7], [9-11].

Area 3: Co-design of the Mocean WEC to reduce unit cost of generated electricity and increase annual energy production (AEP). We have integrated our proposed control strategies into WEC design to find an optimal trade-off between control objectives (e.g. energy output maximisation) and hardware design objectives (e.g. minimisation of the capacities of generators/actuators) for a WEC to reduce the unit cost of energy output. Thus the co-design results provide useful design guidelines at the WEC design stage to achieve an overall optimality of the whole WEC control system. For demonstration purpose, we select the power take-off (PTO) torque limit as the key co-design parameter influencing both control performance and the cost of PTO to demonstrate the efficacy of the co-design approach based on our control strategies. Our simulation results show that when the Mocean WEC is controlled by the MPC controller, there is a **6.9% - 8.2%** decrease of the annual average unit cost of the co-designed WEC, and a **30% - 43%** i increase of AEP.

Area 4: Front-end Engineering Design (FEED). We have outlined the approaches and technical issues for physical demonstration to be conducted in Stage 3 for validation of the proposed AHMPC framework and the associated technologies. The selection of sensors/actuators, and coupling between different subsystems have been fully considered. For the Stage 3 FEED, we have proposed a stepwise risk-managed approach to the Hardware-in-the-Loop (HiL) modelling that builds on the simulation deliverables from QMUL, and uses control codes developed by QMUL and the Mocean numerical hydrodynamic model (MNHM), before we conduct tank testing.

4 Project Achievements

The Stage 2 project went well, with all the targets and the activities described by the work packages fulfilled on time as planned in the Stage 2 application. Essentially, we have made the following achievements:

1) The AHMPC framework and key enabling technologies have been successfully developed for the Mocean WEC which, as a multi-float and multi-motion WEC, presents a much more challenging control platform than that of the single point absorber undertaken by the majority of the WEC control community.

2) The proposed strategies have been fully validated and compared with the existing state-of-the-art techniques based on the Mocean WEC. The computational efficiency has been considered in the controller design to pave the way for the real-time implementation of these control strategies.

3) Key results have been published in the top journal papers and presented in the prestigious conferences in control and renewable energy areas.

4) The front-end engineering design for the Stage 3 hardware testing and tank testing validation has been fully outlined with technical details.

5 Recommendations for Further Work

Our ultimate target is to commercialize the techniques developed in Stage 2. To achieve this target, continuing support from WES on Stage 3 will be indispensible. The physical demonstrations expected in Stage 3 will require a Front-End Engineering Design (FEED) for Hardware in the Loop (HiL). We propose a two-step, de-risking approach to the HiL modelling that builds incrementally on the existing simulation deliverables, on QMUL hardware resources and on wave tank testing of Mocean's scale models that, ultimately, demonstrates both the hydrodynamic and control features in physical form. Beyond Stage 3, we plan to secure extra funding to do sea trial validations. We will also seek opportunities to collaborate with the winners of other WES programmes to extend the applications of our techniques.

6 Communications and Publicity Activity

Some key research outputs have been published in the leading conferences and top journals in control and sustainable energy areas. To avoid disclosure of confidential technical data from this project, we used a popularly studied scaled point absorber [2] for numerical simulations. The following publications (including 4 journals and 2 conferences) have clearly acknowledged the support of Wave Energy Scotland:

S. Zhan, J. Na , G. Li and B. Wang, "Adaptive Model Predictive Control of Wave Energy Converters," *IEEE Transactions on Sustainable Energy (Accepted),* 2018.

S. Zhan, G. Li, J. Na and W. He, "Feedback noncausal model predictive control of wave energy converters," *Control Engineering Practice (Accepted),* Special Issue of Energy Conversion, 2018.

J. Na, G. Li, B. Wang, G. Herrmann and S. Zhan, "Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming," *IEEE Transactions on Sustainable Energy (Published online),* 2018.

J. Na, B. Wang, G. Li and S. Zhan, "Nonlinear Constrained Optimal Control of Wave Energy Converters with Adaptive Dynamic Programming," *IEEE Transactions on Industrial Electronics (Published online),* 2018.

S. Zhan, B. Wang, J. Na and G. Li, "Adaptive Optimal Control of Wave Energy Converters," in *The 11th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS)*, 2018.

S. Zhan and G. Li, " Indefinite feedback MPC with preview information of bounded disturbance" in *IEEE Conference on Decision and Control*, Miami, 2018.

Besides the published papers, we still have a few papers in submission and preparation. We are invited by Springer to write a book on wave energy control.

7 Useful References and Additional Data

[1] S. Zhan, W. He and G. Li, “Robust feedback model predictive control of sea wave energy converters,” in *the 20th IFAC World Congress*, Toulouse, France, 2017.

[2] S. Zhan, H. Huijbert, J. Na and G. Li, “Optimal controller design and constraints analysis of a sea wave energy converter,” in *UKACC 11th International Conference on Control* , Belfast, UK, 2016.

[3] S. Zhan and G. Li, “Linear Optimal Noncausal Control of Wave Energy Converters,” *IEEE Transactions on Control System Technology (Published online),* 2018.

[4] S. Zhan, G. Li, J. Na and W. He, “Feedback noncausal model predictive control of wave energy converters,” *Control Engineering Practice (Accepted),* Special Issue in Energy Conversion, 2018.

[5] S. Zhan and G. Li, “Economic feedback model predictive control of wave energy converters,” *IEEE Transactions on Industrial Electronics (In Submission),* 2018.

[6] S. Zhan, B. Wang, J. Na and G. Li, “Adaptive Optimal Control of Wave Energy Converters,” in *The 11th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS)*, 2018.

[7] S. Zhan, J. Na , G. Li and B. Wang, “Adaptive Model Predictive Control of Wave Energy Converters,” *IEEE Transactions on Sustainable Energy (Accepted),* 2018.

[8] Z. Yu and J. Falnes, “State-space modelling of a vertical cylinder in heave.,” *Applied Ocean Research,* pp. 265-275, 1995.

[9] J. Na, G. Li, B. Wang, G. Herrmann and S. Zhan, “Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming,” *IEEE Transactions on Sustainable Energy (Published online),* 2018.

[10] J. Na, S. Zhan and G. Li, “Online Optimal Control of Wave Energy Converters Via Adaptive Dynamic Programming,” in *American Control Conference*, Milwaukee, 2018.

[11] J. Na, B. Wang, G. Li and S. Zhan, “Nonlinear Constrained Optimal Control of Wave Energy Converters with Adaptive Dynamic Programming,” *IEEE Transactions on Industrial Electronics (Published online),* 2018.

[12] G. Li, G. Weiss, M. Mueller, S. Townley and M. R. Belmont, “Wave energy converter control by wave prediction and dynamic programming,” *Renewable Energy,* pp. 392-403, 2012.

[13] G. Li, “Predictive control of a wave energy converter with wave prediction using differential flatness,” in *54th IEEE Conference on Decision and Control (CDC 2015)*, Osaka, Japan., 2015.

[14] G. Li, “Nonlinear model predictive control of a wave energy converter based on differential flatness parameterisation,” *International Journal of Control,* vol. 90, no. 1, pp. 68-77, 2017.

[15] G. Li and M. R. Belmont, “Model predictive control of sea wave energy converters--Part I: A convex approach for the case of a single device,” *Renewable Energy,* pp. 453-463, 2014.

[16] F. Fusco and J. Ringwood, “Short-term wave forecasting for real-time control of wave energy converters,” *IEEE Transactions on Sustainable Energy,* vol. 1, p. 99–106, 2010.

[17] M. Belmont, J. Christmas, J. Dannenberg, T. Hilmer, J. Duncan and B. Ferrier, “An examination of the feasibility of linear deterministic sea wave prediction in multidirectional seas using wave profiling radar: Theory, simulation, and sea trials,” *Journal of Atmospheric and Oceanic Technology,* vol. 31, p. 1601–1614, 2014.