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

WES Control Systems Stage 3 and Extended Project Public Report

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.

In Stage 3, due to the time limit for tank testing, rather than validate all the algorithms proposed in Stage 1 and Stage 2, e.g. Sliding Mode Observer (SMO), adaptive dynamic programming (ADP), we have experimentally validated the efficacy of the core control algorithms of the proposed control framework and the determinsitic sea wave prediction (DSWP) technique using Mocean's 1/20th attenuator type device in Flowave tank. Two of our novel advanced WEC control methods Linear Non-causal Optimal Control (LNOC) and Model Predictive Control (MPC) were evaluated against the existing resistive control (or passive damping control) with a well-tuned damping parameter as the baseline controller, which is widely adopted by many WEC developers. The tank testing results show that both MPC and LNOC can largely outperform the passive damping controller by increasing upto 4.6 times of more energy output in irregular waves. The controllers also demonstrated sufficient robustness in spreading waves and side waves, which can be commonly encountered in real sea states. The DSWP technique was also shown to be reliable and can produce about 80% correlation accuracy upto 4 seconds in the tank testing experiments. These experimentally validated algorithms play the key roles in the control framework proposed and numerically simulated in Stage 1 and Stage 2. From the very encouraging experimental results, we have gained sufficient confidence in further developing our control technologies for WEC control to significantly reduce the LCOE for a step change at a commercial level.

The team participating the Stage 3 project includes 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 Exeter (for wave prediction, robustness handling, and state estimation) and Mocean Energy Ltd. (for device assembling and deployment).

2 Project Achievements

Two tank testing campaigns were conducted respectively in March-April 2021 and July-August 2021, each consisting of 2 tank preparation days and 5 tank testing days. Figure 1 shows the assembled WEC model equipped with Qualisys at the FloWave tank floor, and Figure 2 shows the WEC during the testing experiments. The incoming wave direction is from right to left. The FloWave tank facilities were thoroughly calibrated by FloWave staff at the beginning of each testing campaign for 2 days, and then further checked in the morning of each testing day to guarantee the waves generated have sufficient accuracy. This has provided us a very reliable platform to make fair comparisons between different WEC controllers. The linear passive damping control was tuned to have the maximum energy output and the same damping ratio was used across all the sea states tested, since the energy conversion efficiency is not sensitive to a certain range of damping ratio values across the sea states. Moreover, because the torque limit of the actuator is a key factor influencing WEC control performance, the same torque limit for the actuator was adopted for all the controllers in all the sea states to ensure the fair comparison of the controllers.

Figure 1 WEC model setup

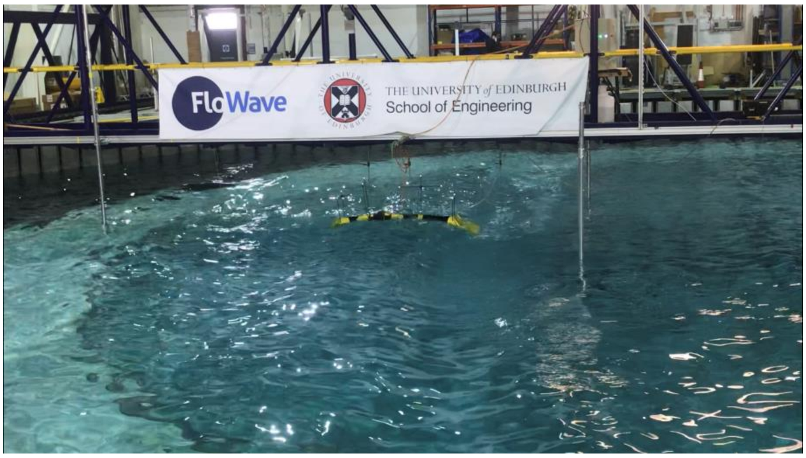

Figure 2 Tank integration for WEC system

The first tank testing was mainly for validating the DSWP technique and LNOC algorithm. Sufficient tank testing data were collected and were used for 1) validation of the hydrodynamic model and 2) derivation of an empirical model by Systems Identification (ID) technique. The first tank testing results show that the LNOC can improve the energy output by 125% over the linear passive damping control. In the second tank testing, we have further modified the WEC control model based on the results from the first tank test. LNOC and MPC controllers were designed based on the new WEC model and then validated by tank testing. The Deterministic Sea Wave Prediction (DSWP) technique was employed to provide wave prediction information to the noncausal optimal controllers. For the scaled sea states generated by FloWave, the DSWP can provide up to a 4 second (about two wave periods) wave prediction with above 80% correlation accuracy. This is a much more accurate prediction over a longer prediction horizon compared to the statistical Autoregressive (AR) prediction method.

Results for uni-directional irregular waves: All the controllers were tested with the same WEC physical model parameter configurations (e.g. the torque limit of the PTO) in seven sea states: irregular waves from IR01 to IR07, from the sea states defined by WES for use in tank testing during the NWEC programme. The control performance comparison in higher sea states from IR08 to IR16 is less relevant because the PTO actuator saturation limit is reached most of the time for the IR06 and IR07 sea states, and all controllers would converge to “bang-bang” control for severely saturated control inputs. The control performance comparison is shown in the following table, where the percentage of energy increase is calculated according to the formula $\frac{E_{control}-E_{baseline}}{E_{baseline}} \times 100\%$ with $E_{control}$ as the energy output by LNOC or MPC and $E_{baseline}$ as the energy output by the baseline controller passive damper:

Sea States	IR01	IR02	IR03	IR04	IR05	IR06	IR07
LNOC	14.09%	65.99%	194.99%	323.32%	53.91%	-3.26%	9.86%
MPC	41.68%	118.65%	333.68%	463.42%	120.15%	9.86%	14.61%

From this table, we see that the significant energy output increase by using LNOC over the baseline control can be up to 3.2 times, and the energy increase by using MPC can be up to 4.6 times. We also found that energy improvement decreases when wave period increases (making the WEC controlled by passive damper away from the resonance frequency) and when wave amplitude increases (leading to more saturated PTO actuation and thus less room for energy improvement by optimal control). Since no fine tuning was conducted for each particular sea state, the LNOC is outperformed by the baseline control in IR06 sea state; however, tuning of LNOC parameters can reverse the result for IR06. This phenomenon also indicates the necessity of adopting an adaptive mechanism to achieve only tuning of the LNOC controller. This table clearly shows MPC outperforms LNOC for all sea states, because MPC can handle saturation limits optimally. This performance improvement is at the cost of extra computational load required to resolve constrained optimisation problem at each sampling time online.

Extra results for side waves and spreading waves: To validate the robustness of the advanced control in real-world sea conditions, the control strategies were tested in more complicated sea states created by the FloWave tank, including two specific cases: 1) a side wave (with an angle of 80 degrees) was imposed onto the original unidirectional wave, 2) a spreading wave with different spreading factors. For the case when IR02 is the dominant incoming wave and IR04 is the side wave, the energy output improvement of LNOC and MPC over passive damping control is respectively 50.10% and 107.80%, which are both slightly smaller than the case without a side wave (c.f. the above Table for the IR02 column: 65.99% and 118.65% respectively). For the case when IR02 is used as a spreading wave with the spreading factor of 20 the energy output improvement of LNOC and MPC over passive damping control is respectively 78.32% and 130.33% which are higher than the unidirectional wave of IR02 without spreading. These results show the robustness of the proposed controllers subject to more complicated sea waves which can be commonly encountered in real sea scenarios.

3 Recommendations for Further Work

We have the following recommendations for future work:

- Complete the full validation of the whole adaptive hierarchical control framework by tank testing. Especially a simple and effective adaptive mechanism suitable for WECs with complicated dynamics needs to be validated. The large wave alarming system to achieve automatic WEC shutdown needs to be validated; this helps significantly enhance the survivability of the WEC during operation in large wave conditions.
- Extend the proposed control strategies to other WECs with different PTOs to demonstrate their transferability. This will attract wider WEC developers to adopt these control strategies in the future.

- Develop the control system for the whole WEC system including energy absorption, power transmission, electricity generation, power conditioning and energy storage. Hardware-in-the-loop dry testing will be needed.
- Develop WEC control algorithms to achieve multiple control objectives, including energy maximisation and peak-to-average ratio reduction.
- Sea trial validation of the control strategies applied to larger scale WECs.
- Develop distributed control strategies for an array of WECs at farm level.

4 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] and also another attenuator called M4, whose data already in public domain, for numerical simulations. We have attended prestigious conferences in control and marine energy to present our latest research results, including: American Control Conference, IFAC World Congress, Asian Wave and Tidal Energy Conference, European Wave and Tidal Energy Conference, International Conference on Renewable Energies Offshore, etc. Queen Mary University of London has also reported the award of our WES project. The following publications (including 12 Q1 top journal papers and 8 conference papers presented in the conferences) have acknowledged the support of Wave Energy Scotland through the 3 Stages:

[1] S. Zhan, J. Na, G. Li and B. Wang, "Adaptive Model Predictive Control of Wave Energy Converters," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 229-238, Jan. 2020, doi: 10.1109/TSTE.2018.2889767.

[2] Y. Zhang and G. Li, "Non-Causal Linear Optimal Control of Wave Energy Converters With Enhanced Robustness by Sliding Mode Control," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2201-2209, Oct. 2020, doi: 10.1109/TSTE.2019.2952200.

[3] S. Zhan, J. Na and G. Li, "Nonlinear Noncausal Optimal Control of Wave Energy Converters Via Approximate Dynamic Programming," in *IEEE Transactions on Industrial Informatics*, vol. 15, no. 11, pp. 6070-6079, Nov. 2019, doi: 10.1109/TII.2019.2935236.

[4] S. Zhan, G. Li and C. Bailey, "Economic Feedback Model Predictive Control of Wave Energy Converters," in *IEEE Transactions on Industrial Electronics*, vol. 67, no. 5, pp. 3932-3943, May 2020, doi: 10.1109/TIE.2019.2922947.

[5] J. Na, B. Wang, G. Li, S. Zhan and W. He, "Nonlinear Constrained Optimal Control of Wave Energy Converters With Adaptive Dynamic Programming," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 10, pp. 7904-7915, Oct. 2019, doi: 10.1109/TIE.2018.2880728.

[6] Siyuan Zhan, Guang Li, Jing Na, Wei He, "Feedback noncausal model predictive control of wave energy converters", *Control Engineering Practice*, Volume 85, 2019, Pages 110-120, ISSN 0967-0661, https://doi.org/10.1016/j.conengprac.2018.12.015.

[7] J. Na, G. Li, B. Wang, G. Herrmann and S. Zhan, "Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming," in *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 961-970, April 2019, doi: 10.1109/TSTE.2018.2856802.

[8] Z. Liao, P. Stansby, G. Li and E. C. Moreno, "High-capacity wave energy conversion by multi-floats, multi-PTO, control and prediction: generalised state-space modelling with linear optimal control and arbitrary headings," in *IEEE Transactions on Sustainable Energy*, doi: 10.1109/TSTE.2021.3082510

[9] Z. Liao, P. Stansby and G. Li, "A generic linear non-causal optimal control framework integrated with wave excitation force prediction for multi-mode wave energy converters with application to M4", *Applied Ocean Research*, vol. 97, 102056, 2020. https://doi.org/10.1016/j.apor.2020.102056

[10]Y. Zhang, T. Zeng and G. Li, "Robust Excitation Force Estimation and Prediction for Wave Energy Converter M4 Based on Adaptive Sliding-Mode Observer," in *IEEE Transactions on Industrial Informatics*, vol. 16, no. 2, pp. 1163-1171, Feb. 2020, doi: 10.1109/TII.2019.2941886.

[11]Z. Liao, N. Gai, P. Stansby and G. Li, "Linear Non-Causal Optimal Control of an Attenuator Type Wave Energy Converter M4," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 3, pp. 1278-1286, July 2020, doi: 10.1109/TSTE.2019.2922782.

[12]Y. Zhang, P. Stansby and G. Li, "Non-causal Linear Optimal Control With Adaptive Sliding Mode Observer for Multi-Body Wave Energy Converters," in *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 568-577, Jan. 2021, doi: 10.1109/TSTE.2020.3012412.

[13] Y. Zhang, S. Zhan and G. Li, Model Predictive Control of Wave Energy Converters with Prediction Error Tolerance, *IFAC World Congress*, 2020.

[14] Y. Zhang and G. Li*, Wave Excitation Force Estimation for Wave Energy Converters Using Adaptive Sliding Mode Observer, *American Control Conference*, Philadelphia, 2019.

[15] Z. Liao and G. Li*, Energy-maximizing control of pitch type wave energy converter M4, *American Control Conference*, Philadelphia, 2019.

[16] Z. Liao and G. Li*, Energy-maximizing control of pitch type wave energy converter M4, American Control Conference, Philadelphia, 2019.

[17] S. Zhan and G. Li*, Indefinite feedback MPC with preview information of bounded disturbance, *the 57th IEEE Conference on Decision and Control (CDC)*, Fontainebleau, Miami Beach, FL, USA on Dec. 17-19, 2018.

[18] S. Zhan, B. Wang, J. Na, G. Li*, Adaptive Optimal Control of Wave Energy Converters, *the 11th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles*, Opatija, Croatia, Sep. 10-12, 2018.

[19] Z. Liao, G. Li and P. Stansby, Linear optimal control on a multi-PTO wave energy converter M4 with performance analysis, Developments in Renewable Energies Offshore: Proceedings of the 4th International Conference on Renewable Energies Offshore, RENEW 2020, Lisbon, Portugal, 12-15 October 2020.

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

Publicity Material

The following journal papers are uploaded.

Filename	Media Type	Description
Adaptive_Model_Predictive_Control_of_Wave_Energy_Converters	Journal paper	S. Zhan, J. Na, G. Li and B. Wang, "Adaptive Model Predictive Control of Wave Energy Converters," in *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 229-238, Jan. 2020, doi: 10.1109/TSTE.2018.2889767.
Non-Causal_Linear_Optimal_Control_of_Wave_Energy_Converters_With_Enhanced_Robustness_by_Sliding_Mode_Control	Journal paper	Y. Zhang and G. Li, "Non-Causal Linear Optimal Control of Wave Energy Converters With Enhanced Robustness by Sliding Mode Control," in IEEE Transactions on Sustainable Energy, vol. 11, no. 4, pp. 2201-2209, Oct. 2020, doi: 10.1109/TSTE.2019.2952200.
Nonlinear_Noncausal_Optimal_Control_of_Wave_Energy_Converters_Via_Approximate_Dynamic_Programming	Journal paper	S. Zhan, J. Na and G. Li, "Nonlinear Noncausal Optimal Control of Wave Energy Converters Via Approximate Dynamic Programming," in IEEE Transactions on Industrial Informatics, vol. 15, no. 11, pp. 6070-6079, Nov. 2019, doi: 10.1109/TII.2019.2935236.
Economic_Feedback_Model_Predictive_Control_of_Wave_Energy_Converters	Journal paper	S. Zhan, G. Li and C. Bailey, "Economic Feedback Model Predictive Control of Wave Energy Converters," in IEEE Transactions on Industrial Electronics, vol. 67, no. 5, pp. 3932-3943, May 2020, doi: 10.1109/TIE.2019.2922947.
Nonlinear_Constrained_Optimal_Control_of_Wave_Energy_Converters_With_Adaptive_Dynamic_Programming	Journal paper	J. Na, B. Wang, G. Li, S. Zhan and W. He, "Nonlinear Constrained Optimal Control of Wave Energy Converters With Adaptive Dynamic Programming," in IEEE Transactions on Industrial Electronics, vol. 66, no. 10, pp. 7904-7915, Oct. 2019, doi: 10.1109/TIE.2018.2880728.
Feedback_noncausal_model_predictive_control_of_wave_energy_converters	Journal paper	Siyuan Zhan, Guang Li, Jing Na, Wei He, "Feedback noncausal model predictive control of wave energy converters", *Control Engineering Practice*, Volume 85, 2019, Pages 110-120, ISSN 0967-0661, https://doi.org/10.1016/j.conengprac.2018.12.015
Robust_Optimal_Control_of_Wave_Energy_Converters_Based_on_Adaptive_Dynamic_Programming	Journal paper	J. Na, G. Li, B. Wang, G. Herrmann and S. Zhan, "Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming," in IEEE Transactions on Sustainable Energy, vol. 10, no. 2, pp. 961-970, April 2019, doi: 10.1109/TSTE.2018.2856802.

Filename	Media Type	Description
High-capacity_wave_energy_conversion_by_multi-floats_multi-PTO_control_and_prediction_generalised_state-space_modelling_with_linear_optimal_control_and_arb	Journal paper	Z. Liao, P. Stansby, G. Li and E. C. Moreno, "High-capacity wave energy conversion by multi-floats, multi-PTO, control and prediction: generalised state-space modelling with linear optimal control and arbitrary headings," in IEEE Transactions on Sustainable Energy, doi: 10.1109/TSTE.2021.3082510
A generic linear non-causal optimal control framework integrated with wave excitation force prediction for multi-mode wave energy converters with application to M4	Journal paper	Z. Liao, P. Stansby and G. Li, “A generic linear non-causal optimal control framework integrated with wave excitation force prediction for multi-mode wave energy converters with application to M4”, Applied Ocean Research, vol. 97, 102056, 2020. https://doi.org/10.1016/j.apor.2020.102056
Robust_Excitation_Force_Estimation_and_Prediction_for_Wave_Energy_Converter_M4_Based_on_Adaptive_Sliding-Mode_Observer	Journal paper	Y. Zhang, T. Zeng and G. Li, "Robust Excitation Force Estimation and Prediction for Wave Energy Converter M4 Based on Adaptive Sliding-Mode Observer," in IEEE Transactions on Industrial Informatics, vol. 16, no. 2, pp. 1163-1171, Feb. 2020, doi: 10.1109/TII.2019.2941886.
Linear_Non-Causal_Optimal_Control_of_an_Attenuator_Type_Wave_Energy_Converter_M4	Journal paper	Z. Liao, N. Gai, P. Stansby and G. Li, "Linear Non-Causal Optimal Control of an Attenuator Type Wave Energy Converter M4," in IEEE Transactions on Sustainable Energy, vol. 11, no. 3, pp. 1278-1286, July 2020, doi: 10.1109/TSTE.2019.2922782.
Non-causal_Linear_Optimal_Control_With_Adaptive_Sliding_Mode_Observer_for_Multi-Body_Wave_Energy_Converters	Journal paper	Y. Zhang, P. Stansby and G. Li, "Non-causal Linear Optimal Control With Adaptive Sliding Mode Observer for Multi-Body Wave Energy Converters," in IEEE Transactions on Sustainable Energy, vol. 12, no. 1, pp. 568-577, Jan. 2021, doi: 10.1109/TSTE.2020.3012412.

Extended Control Project

Public Report

Prof Guang Li

This project has been supported by Wave Energy Scotland

1 Introduction

This project aims to develop a simple yet effective adaptive mechanism to directly switch advanced model-based optimal controllers adaptively according to the change of sea states. The control scheme is suitable for different types of WECs with complicated dynamics. An adaptive switching law is designed to switch the optimal controllers to maintain the optimal performance in different sea states. The sea states need to be identified in real time based on wave prediction information. This work is motivated by our recently finished tank testing experiments of two predictive controllers, Linear Non-causal Optimal Control (LNOC) and Model Predictive Control (MPC), which were designed and validated on a hinged attenuator wave energy converter (WEC) called BlueStar developed by Mocean Energy Ltd. Both controllers were validated to significantly improve the energy outputs in a range of irregular sea states defined by WES compared with the baseline controller, a passive damping control with optimally tuned passive damping ratio. The controllers were also tested to be robust to side waves and spreading waves. These promising results show the great potentials of our non-causal optimal control strategies, and the main results were published in a series of 3 journal papers recently, [i]-[iv] as listed in Section 6.

Though the advanced controllers can exhibit satisfactory performance over a range of sea states, the control performance can potentially degrade when the sea state changes significantly. This motivates us to adaptively tune the controllers when sea state characteristics change too much resulting in degraded performance of the controller. One method is to online identify the WEC model and then adaptively tune the controllers based on the changing parameters. Another method is to adaptively tune the controller parameters based on the online measurement of the WEC responses and the sea states. We have previously done some research work in this direction and used a point absorber as a case study [1]-[3]. However, both methods can be challenging for design and real-time implantation for WECs with much more complicated dynamics than that of point absorbers.

2 Description of Project Technology

To circumvent the difficulties, we propose a switching adaptive control scheme to realise the automatic switching of controllers, which have been previously designed and validated in different range of sea states. This will enable the controller to maintain high performance and reliability across a large range of sea states, which can be commonly encountered in real sea conditions. The development of this control scheme involves the combination of several techniques, such as the system identification, sea state identification, switching law design, and controller design. Though the design stage can be involved, the implementation of the scheme is straightforward and reliable.

3 Scope of Work

The scope of the work involves:

1) System identification of the WEC models in different sea states. The fidelity of the models was analysed and compared.

2) LNOC controllers were designed based on the validated models in 1), and then tuned and tested in the tank testing experiments.

3) The functionality of the switching law based on the online sea wave identification technique was validated.

4) The efficacy of the switching control scheme is validated in tank testing experiments.

4 Project Achievements

We have experimentally demonstrated the efficacy of the scheme using an attenuator WEC model named as Blue Horizon developed by Mocean Energy Ltd as a case study using the FloWave tank facilities of Edinburgh University. Due to the time limit, we only tested the scheme when it is combined with the LNOC controller. The experimental results show that the switching control method can further improve the energy output. For example, one set of testing results show that the energy output of the WEC model can be improved by 65% when using LNOC alone as compared with the case when a well-tuned passive damper is employed, and the improvement can be increased to 100% when the proposed switching scheme is used in a testing involving two combined sea states. Other types of controllers, e.g., MPC, can also be embedded into the scheme to further enhance their performance. In general, the application of the proposed control scheme has the potential to further improve the WEC control system's stability, robustness, and survivability in real sea conditions.

5 Recommendations for Further Work

Due to the time limit, we only tested the scenario with unidirectional waves. The more complicated cases involving multiple directional waves and spreading waves were not tested due to time limitations. However the robustness of the LNOC and MPC controllers in these complicated sea conditions have been validated in our Stage 3 control project. Thus we assume the robustness properties in these sea conditions can be inherited by these controllers are embedded into the proposed switching control scheme. Nevertheless, it is worth testing the switching control scheme experimentally in the future.

Development of indirect or direct adaptive controllers for WECs with complicated dynamics is definitely worth pursuing in the long term, though it is outside the scope of this project due to time constraints.

6 Communications and Publicity Activity

We have been actively disseminating the latest research outputs from our WES control projects in academic conferences and international workshops. 4 publications were released to public domain recently, including 3 journal papers and 1 conference paper as listed in the Section of Publication Material. The conference paper was presented in an invited session in the IFAC conference in September 2022.

[i] Zhijing Liao, Tao Sun, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Zhenchun Wang, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter - Part I: Experiment setup and control-oriented modelling, *IEEE Transactions on Sustainable Energy,* doi: 10.1109/TSTE.2023.3246172.

[ii] Zhijing Liao, Tao Sun, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Zhenchun Wang, Siyuan Zhan, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter - Part II: Linear noncausal optimal control and deterministic sea wave prediction tank testing, *IEEE Transactions on Sustainable Energy*, doi: 10.1109/TSTE.2023.3246173.

[iii] Tao Sun, Zhijing Liao, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Siyuan Zhan, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter – Part III: Model predictive control and robustness validation, *IEEE Transactions on Sustainable Energy*, doi: 10.1109/TSTE.2023.3246171.

[iv] Zhijing Liao, Tao Sun, Mustafa Al-Ani, Laura-Beth Jordan, Christopher Edwards, Michael Belmont, Guang Li, Tank testing experiment of the Mocean M100 wave energy converter: linear non-causal optimal control and wave prediction, IFAC-PapersOnLine, 2022, Vol 55, Issue 31, Pages 339-344, 2022.

7 Useful References and Additional Data

[1] S. Zhan, J. Na , G. Li and B. Wang, Adaptive Model Predictive Control of Wave Energy Converters, *IEEE Transactions on Sustainable Energy*, vol.11(1), pp. 229-238, 2020. DOI: 10.1109/TSTE.2018.2889767

[2] J. Na, B. Wang, G. Li, S. Zhan, and W. He, Nonlinear Constrained Optimal Control of Wave Energy Converters with Adaptive Dynamic Programming, *IEEE Transactions on Industrial Electronics*, vol 66(10), pp 7904 - 7915, 2019. DOI: 10.1109/TIE.2018.2880728

[3] J. Na, G. Li, B. Wang, G. Herrmann, S. Zhan, Robust Optimal Control of Wave Energy Converters Based on Adaptive Dynamic Programming, *IEEE Transactions on Sustainable Energy*, vol.10(2), 961 - 970, 2019. DOI: 10.1109/TSTE.2018.2856802

Publicity Material

[Please supply WES with any logos, images and video files that are non-confidential and available for WES to use to promote WES supported projects. Files should be uploaded to the Objective Connect milestone folder. Use the table below to summarise the publicity material.]

Filename	Media Type	Description
WEC Control-Part 1	PDF file	Journal paper: Zhijing Liao, Tao Sun, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Zhenchun Wang, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter - Part I: Experiment setup and control-oriented modelling, *IEEE Transactions on Sustainable Energy,* doi: 10.1109/TSTE.2023.3246172.
WEC Control-Part 2	PDF file	Journal paper: Zhijing Liao, Tao Sun, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Zhenchun Wang, Siyuan Zhan, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter - Part II: Linear noncausal optimal control and deterministic sea wave prediction tank testing, *IEEE Transactions on Sustainable Energy*, doi: 10.1109/TSTE.2023.3246173.
WEC Control-Part 3	PDF file	Journal paper : Tao Sun, Zhijing Liao, Mustafa Al-Ani, Laura-Beth Jordan, Guang Li, Siyuan Zhan, Michael Belmont, Christopher Edwards, Modelling and control tank testing validation for attenuator type wave energy converter – Part III: Model predictive control and robustness validation, *IEEE Transactions on Sustainable Energy*, doi: 10.1109/TSTE.2023.3246171.
M100 Tank Testing - IFAC conference	PDF file	Conference paper: Zhijing Liao, Tao Sun, Al-Ani Mustafa, Laura-Beth Jordan, Chirstopher Edwards, Michael Belmont, Guang Li, Tank testing experiment of the Mocean M100 wave energy converter: linear non-causal optimal control and wave prediction, IFAC-PapersOnLine, Volume 55, Issue 31, 2022, Pages 351-356, ISSN 2405-8963, https://doi.org/10.1016/j.ifacol.2022.10.478.