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

WES Control Systems Stage 1 Public Report

Queen Mary University of London

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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, so that it can be equipped with several important features: maximum energy output subject to constraints, robustness to modelling uncertainties, and survivability in different sea states. Specifically, we will use a deterministic sea wave prediction (DSWP) technique to predict the incoming waves, and this information will be used to determine the sea state and provide non-causal feedforward information to model predictive control (MPC) to improve performance. According to the sea state, a weighting function will be tuned for the MPC controller and the WEC model will also be adaptively updated, so that the optimal performance of the MPC controller can be maintained over a wide range of sea states. This framework combines the strengths of MPC, adaptive control and DSWP technique and thus outperforms the strength of any single MPC or adaptive control strategy. This control framework will be developed for generic types of WECs, but we will use a typical attenuator type of WEC as a case study and its efficacy will be experimentally validated using an efficient and economically viable test rig.

The team include members with complementary expertise in control, wave prediction and wave device design etc. from Queen Mary University of London (for MPC framework development), University of Exter (for wave prediction and robustness handling) 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 model predictive control (MPC) at various sea states so as to significantly improve the potential application of MPC to wave energy converters (WECs). The proposed control framework is anticipated to have more benefits than the existing WEC control strategies. It will have its roots in our previous works [1-10]. Compared with MPC for WEC control, which is 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. Compared with the adaptive control for WEC, the framework can explicitly incorporate 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 normally include actuator constraint and float motion constraint. 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 will be inherited by the proposed AHMPC framework to explicitly incorporate constraints into energy maximisation.
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. A recently developed effective adaptive parameter estimator (APE) [5] will be employed and specifically tailored for WEC dynamic parameter estimation problem.
3. **Handling dynamic uncertainties**. To enhance the robustness of the proposed control framework, we will seamlessly integrate robust control strategies to cope with the unavoidable modelling uncertainties prevalent in WEC models.

4. **Non-causal control with reliable wave prediction 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 will 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 [6,7].
5. **Fast optimisation algorithm**. Fast optimisation algorithms will be specifically tailored for this framework to enable implementation of the proposed control on economically viable computational hardware.
6. **Tuning guideline to guarantee stability**. Although we are not developing rigorous theoretical proof for the stability of the proposed AHMPC framework due to the time limit, we will provide a guideline to tune the AHMPC for stability, which can be straightforwardly followed.

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 [8-10]; 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.

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, energy conversion efficiency, manufacturability, integratability and installability, etc, so that the levelised cost of energy (LCOE) of wave energy can be reduced significantly.

3 Scope of Work

The work undertaken during Stage 1 project include the following activities:

1. **Literature review.** Although a literature review has been done before the Stage 1 application, a more thorough literature review was further undertaken by the team members with extra contributions from the lead investigator's PhD students. Through the literature review, we find that the proposed control framework is novel, has the promise to significantly reduce the levelised cost of energy (LCOE) of wave energy, and is realistically achievable.
2. **Propose the control system framework.** We proposed the AHMPC framework and specified the key functionalities of the components embedded into the framework and the technologies enabling these functionalities, so that the overall key performance of the AHMPC can be achieved.
3. **Preliminary research on the proposed strategies.** To show the promise of the proposed concepts, we have done some initial research work to test the efficacy of several key technologies to be used in this project in both theoretical development and numerical simulation demonstration.
4. **Collaboration with academic/industrial partners.** The team members have effectively collaborated on the activities described in the Work Packages (WPs) in Stage 1 by emails, teleconferences, and meetings. Especially, the lead investigator Dr Li has discussed extensively with co-investigators Prof Michael Belmont in Exeter University regarding the integration of the Deterministic Sea Wave Prediction (DSWP) technique and the technology transfer of DSWP from other projects. Dr Li discussed with Prof Christopher Edwards in Exeter University regarding the robustness enhancement of the proposed framework using sliding mode

control concept. We think some research outputs from an ongoing EPSRC funded project can be transferred to the research of this project. Dr Li discussed with Dr Chris Retzler and Dr Cameron McNatt in the Mocean Energy Ltd specific technical details of the wave energy converter developed by them to fulfil the activity requirements of the WP3. They have shared the technical report on the governing equations of the device and the SIMULINK files.

5. **External collaborations.** During the Christmas period, the PI has visited his oversea collaborator Prof Wei He (Beijing University of Science and Technology) sponsored by the Royal Society Newton Advanced Fellowship project on "Control of floating wave energy converters with mooring systems" and Prof Jing Na in (Kunming University of Science and Technology) sponsored by the Royal Society Newton Exchange Programme project on "Fast adaptive optimal control with application to sustainable energy systems". These visits were very fruitful and some key research outputs can be directly transferred to this project. For example, the adaptive parameter estimation algorithm and also the adaptive dynamic programming algorithm developed for those projects with demonstrated efficacy. This ambitious project will be significantly supported by our collaborators and PhD students and enhanced by technology transfers from other ongoing projects.

4 Project Achievements

The Stage 1 project went well and the activities described by the work packages were undertaken, including a thorough literature review of the proposed research topic, a full definition and feasibility study of the proposed AHMPC framework, and extensive communication, collaboration with the industrial partner Mocean Energy Ltd regarding the dynamic modelling and control issues of their WEC and the preparation of the full proposal for the Stage 2 application. Besides the necessary research outputs required by the Stage 1 work packages, we have even done some preliminary research beyond the Scope of Stage 1, which provides us with a good starting point for Stage 2 research. For example, to demonstrate efficacy of the core concept of the proposed framework, we have developed an adaptive parameter estimation (APE) method specifically tailored for the WEC system identification problem. Integration of this novel APE method to a linear optimal control strategy can improve the energy output for a point absorber by 7% for a moderate sea state and 15% for a sea state with changing dominant frequency over a broader wave spectrum. As another key technology to provide robustness for the framework, we have also demonstrated that sliding mode observer can effectively cope with modelling uncertainties and provide much more accurate state estimation than the classical Kalman observer in the WEC control problem. These research outputs are to be submitted to key journal and conferences in Renewable Energy and Conferences as summarised in Section 6.

5 Recommendations for Further Work

To further expedite the progress of the work, we think it would be very supportive if we can recruit some postdoctoral researchers to exclusively work on this project, although some PhD students can still get involved in the project to make their own contributions. More collaborations with industrial companies in sensors/actuators/power electronics and organisations with tank testing facilities could be helpful towards final commercial implementation.

6 Communications and Publicity Activity

WES Annual Conference attendance: We have attended the WES annual Conference in Nov 2017 and presented the project poster during the event. We discussed with other teams and introduced our project to attendees.

To disseminate the preliminary research outputs, several papers are being prepared. Some of the concept to be used in this project has been demonstrated in a recent work, which is to be submitted for publication. Useful References and Additional Data

7 Useful References and Additional Data

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