Nonlinear Optimal Control: Concepts, Practicalities and Benefits

WES Control Systems Stage 1 Public Report

Industrial Systems and Control Ltd

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1 Project Introduction

The performance of the control in WEC systems is central to extracting as much of the available power as possible over the widest range of sea states while ensuring long term survivability in extreme conditions. Linear control (classical or linear optimal), which has been the mainstay as WEC control strategies, tends to address many of the inherently nonlinear control challenges in ad-hoc ways, resulting in sub-optimality and control systems that are laborious to develop and not readily transferable, and potentially problematic operations if not fully understood or evaluated.

This project aimed to demonstrate the feasibility of using nonlinear optimal control methods such as nonlinear model predictive control (NMPC) that have been gaining maturity in other industries, such as automotive and wind, for wave energy devices. The potential of nonlinear optimal control was evaluated and quantified using simulation studies. Considerations were also given to how nonlinear control can be extended to address the broader range of control challenges within the WES landscape.

The project team consisted of Industrial Systems and Control Ltd (ISC), Mocean Energy and Pelagic Innovation Ltd. ISC was the lead contractor carrying out the feasibility study and Mocean and Pelagic provided advice on representative ocean conditions and other application knowledge relevant to WEC controls.

ISC was established in 1997 to address the needs of control and modelling for challenging industrial applications. Since then its team of full-time consultant engineers have been delivering valuable projects in the automotive, oil/gas, nuclear, renewables and marine industries. ISC takes pride in its unique ability to investigate challenging control problems from a state-of-the art theoretical perspective combined with highly practical experience of getting control working in the field. Our first-class engineers are highly skilled in control and dynamic simulation, and strive to deliver the very best for our clients. ISC engineers have worked on many commercial contract and UK/EU grant funded research projects over the years, so are well versed with the challenges in taking advanced control from the very earliest stages through the Technical Readiness Levels (TRL). We have published over 15 peer reviewed papers on the NMPC related work (see [1][2][3][4], for example). ISC also has its own MATLAB/Simulink toolbox of the control methods to facilitate investigation on WEC applications, which has proven to be a key to delivering useful results within the scope of this Stage 1 project.

Mocean Energy was formed in July 2015 to develop the Mocean wave energy converter (WEC), an asymmetric hinged raft designed to promote the cross-coupling between its degrees of freedom to increase and broaden its response in waves. Mocean has a wealth of experience in physical and numerical modelling that is relevant to the development of control strategies, in particular a detailed understanding of the behaviour of its own WEC. The company is currently contracted to WES under NWEC Stage 2 to develop a Front End Engineering Design (FEED) and an in-depth familiarity with the Power Take-Off (PTO), its capabilities and limitations, knowledge that are beneficial to the advancement of this control project.

Pelagic Innovation is the consultancy company of Donald Naylor who is a Chartered Mechanical Engineer with 20 years of experience in the design, manufacture, installation and operation of powerful equipment for the marine environment, including wave energy devices. Donald has a broad knowledge of mechanical systems, hydraulics, structures, composites, marine operations and other associated technologies as well as being an experienced manager of technical specialists, suppliers and customers.

2 Description of Project Technology

As an advanced control method, nonlinear optimal control such as nonlinear model predictive control (nonlinear MPC, or NMPC) derives the control actions for a given nonlinear system to meet a defined optimality criterion. Typically, the process involves finding the optimal control actions that minimise a defined cost function, usually subject to certain constraints. An internal model (of a nonlinear nature) is used to predict the system behaviour from the current to a future point of time defined by a prediction horizon. The solution of this optimisation problem contains the sequence of ideal control actions for the current time up to the prediction horizon, the first of which is applied to the system only. This process is repeated at the next sample time (and so on) to determine the best control action with new measurement and new prediction over the prediction horizon, a concept termed receding horizon.

Originated in industry some 40 years ago, MPC found good adoption initially in industries with relatively slow processes and used linear models for the high-level co-ordination and optimisation of the many low level regulatory control loops. In recent years, as the power of computer hardware has increased rapidly and commercial off-the-shelf tools became available, it has started to be applied to embedded control applications with faster dynamics e.g. servomechanisms [5] and automotive engineering [1][2][3].

MPC is popular for several reasons, including [5]:

- Being the only generic control method that can handle practical constraints such as equipment and safety constraints (thus allowing plant operation closer to limits);
- Easy extension to multivariable plants;
- More capable than proportional-integral-derivative (PID) control (even when no constraints are involved), but not that much harder to tune (even on difficult loops, e.g. those with long time delays).

3 Scope of Work

The main objective of this Stage 1 project was to carry out preliminary investigation into the feasibility of advanced control methodology such as NMPC for the low-level real-time control functions within a WEC/PTO system. For this purpose, a specific NMPC formulation called nonlinear generalised predictive control (NGPC) was used with linear parameter-varying (LPV) models to represent the nonlinear system. It was selected for the following reasons:

- Compared with the classical feedback control design method that uses a linear time invariant (LTI) model, it can provide better performance and be more robust over a wider range of operating conditions;
- It requires minimal tuning parameters amongst the various MPC implementations;
- ISC has significant experience in deriving control-orientated LPV models from physics-based models which is recognised as a key technical challenge in deploying this type of controller in WEC systems;
- ISC has:
    - Substantial understanding of the method both on the theory and the practical application side having undertaken many years of valuable research and development for the automotive and wind energy industries;
    - In-house MATLAB/Simulink advanced control design toolbox (including NGPC) available to facilitate this project and deliver useful outcomes efficiently.

The focus of the project was on the low-level real-time control of WEC systems, i.e. where the control actions are derived at each sample to optimise the cost function arising from the nonlinear models and varying operating points that represent the system.

4 Project Achievements

The project has achieved its proposed objectives through a simulation based quantitative analysis of the key performance and survivability indicators of a nonlinear model predictive controller (NMPC) in comparison with a baseline proportional-integral (PI) controller on a simplified point absorber model, combined with a qualitative assessment of the potential benefits of the proposed method in tackling other WEC control challenges.

In particular, the following have been accomplished:

- Quantification of power capture potential compared with a baseline controller;
- High-level consideration of the broader WEC control challenges, in particular nonlinearities, and qualitative assessment on how the proposed method can approach these challenges and the potential benefit;
- Consideration of the additional requirements for practical implementation of the proposed method.

The proposed method has been shown to offer benefits to WEC control, including:

- **Improving performance** - In the simulation study carried out, the average improvement by the NMPC over the baseline controller on total power captured across a spectrum is between 8 and 20% depending on sea states, while the maximum improvement observed was 54%;
- **Operations at or beyond WEC/power take-off (PTO) constraints –** The method is particularly suited to handle a variety of nonlinearities found in WEC systems, whether due to device dynamic characteristics or hard or soft motion constraints, as they can be incorporated directly into the NMPC optimisation framework as demonstrated in the simulation results. Further, improvements in power capture are still possible at the same time as maximising survivability when constraints are active (which is common in WEC), by using a cost function that maximises both the power capture and survivability. For example, the simulation study demonstrated that, when constraints were active, both a 7.8% increase in power capture and 82% reduction in the peak-to-peak force were achieved;
- **Real-time trading-off between control criteria -** The simulations demonstrated that it is possible to change the prioritisation between power capture and survivability within a properly defined optimisation problem. Reductions between 68 and 83% in the peak-to-peak PTO force were possible with trade-offs in the power captured. However, it was only for the most extreme case that the power capture dropped significantly.

These ultimately lead to a corresponding improvement in the overall **levelized cost of energy** (LCOE) and **survivability**.

Furthermore, the following assessments/observations have been established concerning the practical implementation of the proposed control method:

- **Time delays** – Time delays are an important limiting factor in control performance. NMPC can incorporate time delays directly, instead of accepting lower performance as is the case with most other control methods.
- **Sensors** – Overall, NMPC places no more demand on the availability of sensors than a classical PI controller. Although in general NMPC relies on the knowledge of all states, some of which are impractical to measure by actual (hardware) sensors for various reasons, estimations of these states by e.g. a Kalman filter and the system models are common with such controllers.
- **Modelling** – NMPC requires a reasonably good model of the actual WEC system. Despite the challenges involved in deriving such a model from available sources (CFD/hydrodynamic model, practical data from various experimental sources, etc.), modelling experience is invaluable to ease the process and is transferable across industrial applications of similar complexity.

- **Robustness** – Owing to the use of a receding horizon, NMPC has a good degree of robustness built in allowing it to tolerate some plant-model mismatch. Further, as was seen from the simulation study, NMPC remained robust and preserved performance over a much wider range of operating conditions than a simple fixed gain controller which must be detuned to ensure robustness.
- **Computational requirements** – NMPC has a higher computational burden than conventional linear controllers, affected by the choices of parameters such as the model order and prediction horizon. However, today's real-time targets can run such algorithms at the sample rates needed for this application. Ultimately, the control designer needs to balance specific needs of WECs and design and application experience is, again, helpful and transferable.

As an added benefit, a good model derived for control design can be used to enhance other aspects of the WEC engineering process, e.g. in design and commissioning, resulting in a shorter engineering time thus lowering the **CAPEX** and improving **affordability**.

As a Stage 1 project, the feasibility study carried out has been limited in scope and depth.

5 Recommendations for Further Work

As a Stage 1 project, the feasibility study carried out has been limited in scope and depth. It is therefore recommended that a Stage 2 project be undertaken to:

- Formulate the best framework for NMPC use within WEC/PTO applications, considering not only optimisation of the real-time power capture by the PTO and survivability, but also wider system performance and also practical implementation considerations;
- Investigate the key nonlinearities in actual WEC and PTO being developed to understand how they should be handled by the real-time control, and the implications on performance arising from approximations, plant-model mismatch and sensor limitations;
- Formalise the benefits for real world situations within a comprehensive and rigorous simulation, both for a generic point absorber and a specific floating attenuator WEC/PTO;
- Demonstrate how the controller models can be derived from the models that WEC/PTO developers typically utilise, and how such models are refined through the device development process and into service;
- Develop a Stage 3 project plan for developing, implementation and testing on the project partner's specific WEC/PTO.

6 Communications and Publicity Activity

The work was promoted at the WES Annual Conference, Edinburgh, on 28 November 2017.

7 Useful References and Additional Data

[1] P. Majecki, M. J. Grimble, I Haskara, Y Hu, C.F. Chang, Total Engine Optimization and Control for SI Engines Using Linear Parameter-Varying Models, 2017 American Control Conference, Seattle, WA, USA on May 24 - 26, 2017.

[2] P. Majecki, G. van der Molen, I. Haskara, Y. Hu, C.F. Chan and M. J. Grimble, Real-Time Predictive Control for SI Engines Using Linear Parameter-Varying Models, 5th IFAC Conference on Nonlinear Model Predictive Control, Seville, Spain, pp.94-101, 17-20 Sept 2015.

[3] A. Dutka, H. Javaherian, M. J. Grimble, Model-based nonlinear multivariable engine control, *2007 American Control Conference*, New York, NY, USA, pp. 3671-3677, 2007.

[4] P. Savvidis, M. J. Grimble, M. Majecki, Y. Pang, Nonlinear Predictive Generalised Minimum Variance LPV Control of Wind Turbines, International Conference on Renewable Power Generation, September 2016.

[5] J. M. Maciejowski, Predictive Control with Constraints, Prentice Hall, 2002.

[6] N. Tom and R. W. Yeung, Non-linear model predictive control applied to a generic ocean-wave energy extractor, Proc. of the ASME 2017 32nd Int. Conf. on Ocean, Offshore and Arctic Engineering (OMAE2013), June 9-14, 2013, Nantes, France.