CONTROL SYSTEMS

ANNUAL CONFERENCE 2017
STAGE 1 PROJECT POSTERS

WES_CS11_AC17_Posters

Revision	Date	Purpose of issue	Issued By
1.0	28/11/2017	Presentation	Stage 1 Participants
2.0	04/01/2019	Collation into one document	Wave Energy Scotland

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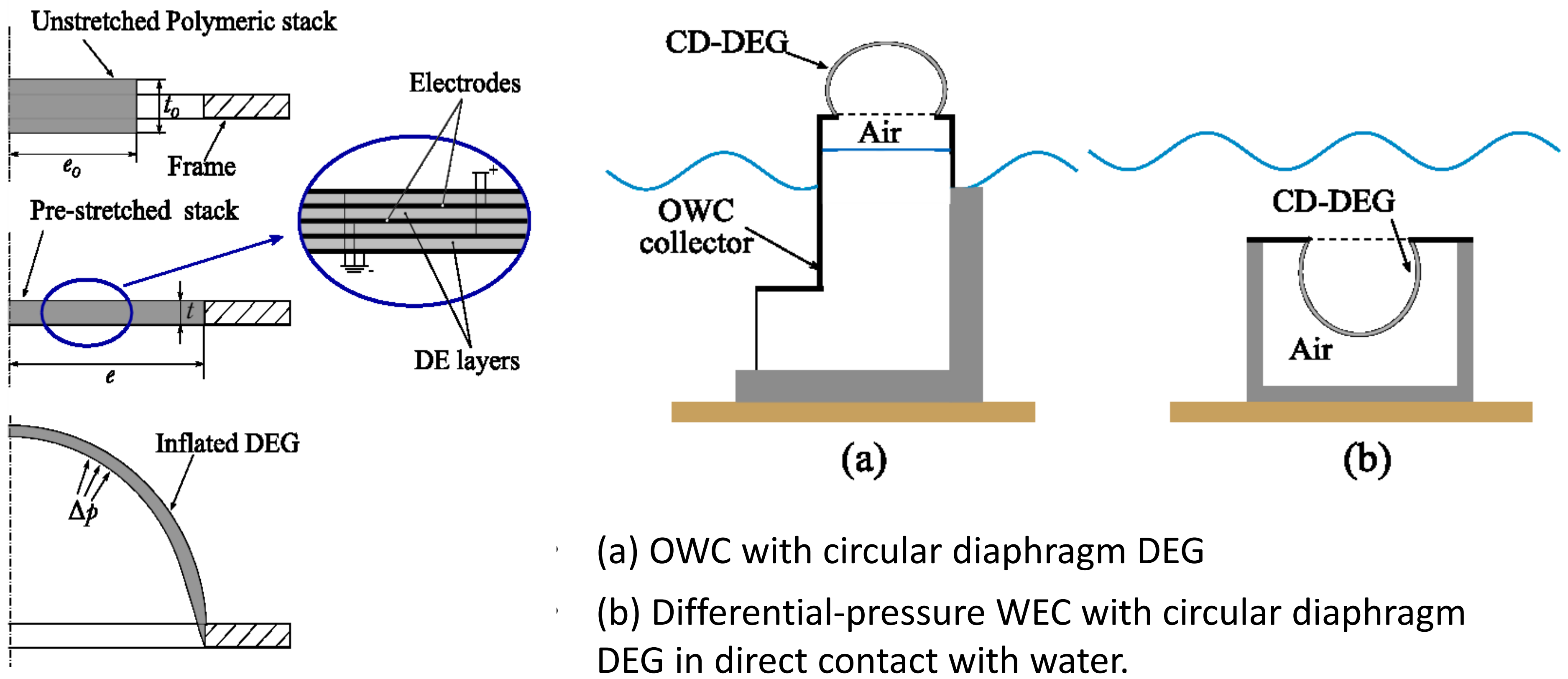
Control of Dielectric Elastomer Generator PTO

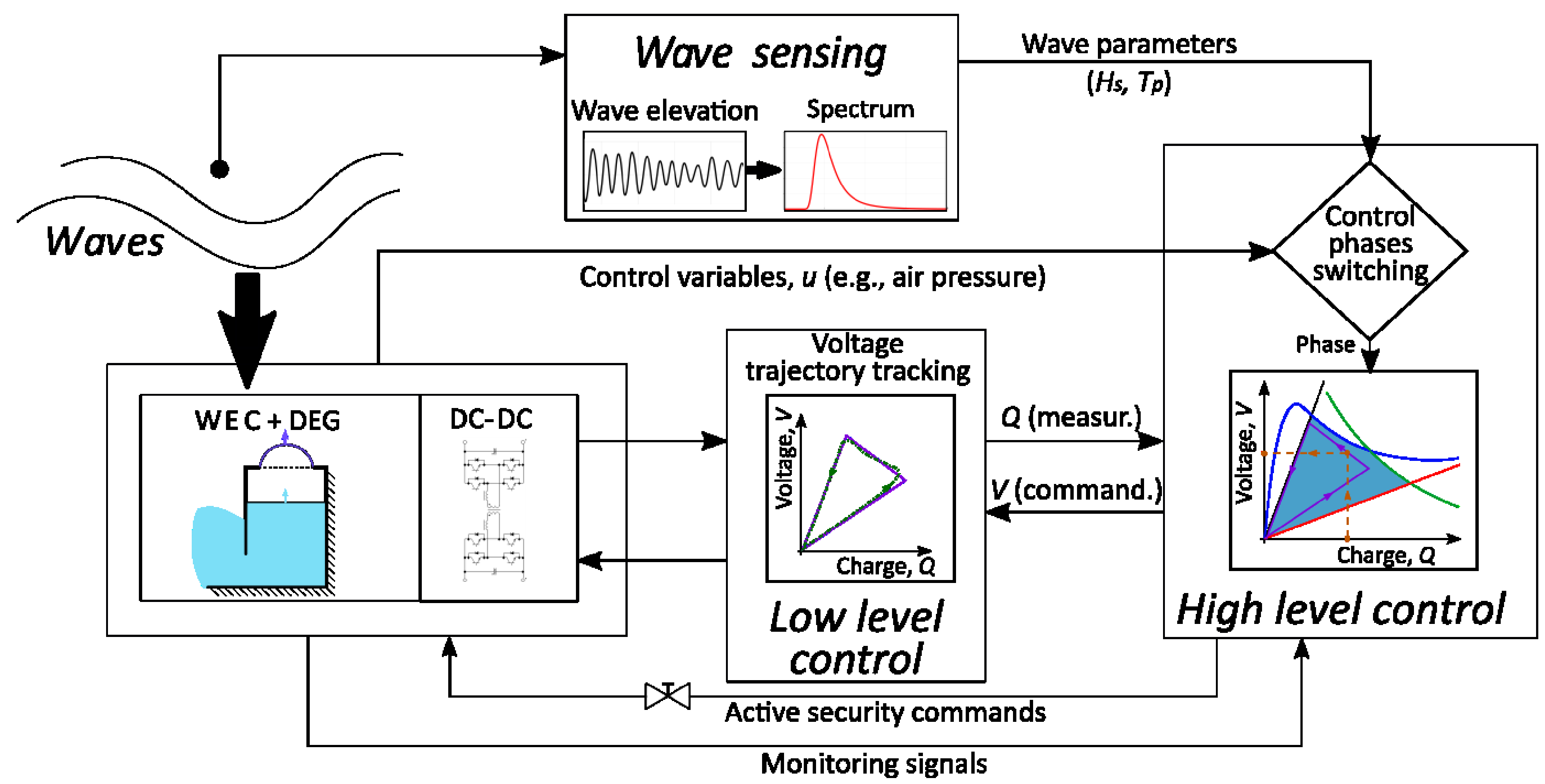
G. Rosati Papini, G. Moretti, F. Damiani, D. Crooks, D. Forehand, G. François,
R. Vertechy, L. Zaccarian, M. Fontana

Dielectric Elastomer Generator (DEG) PTO

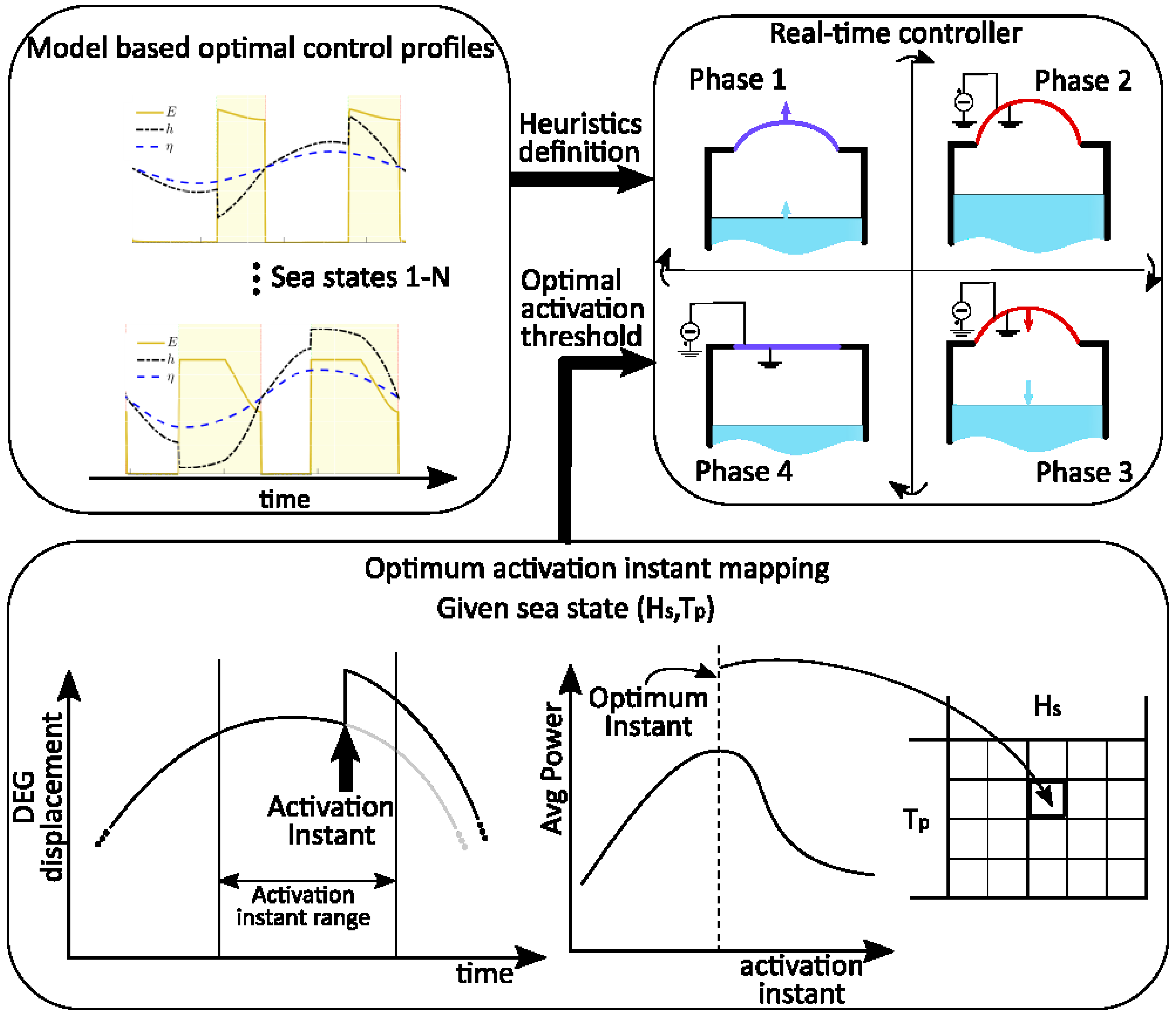


- (a) OWC with circular diaphragm DEG
- (b) Differential-pressure WEC with circular diaphragm DEG in direct contact with water.

Control system architecture



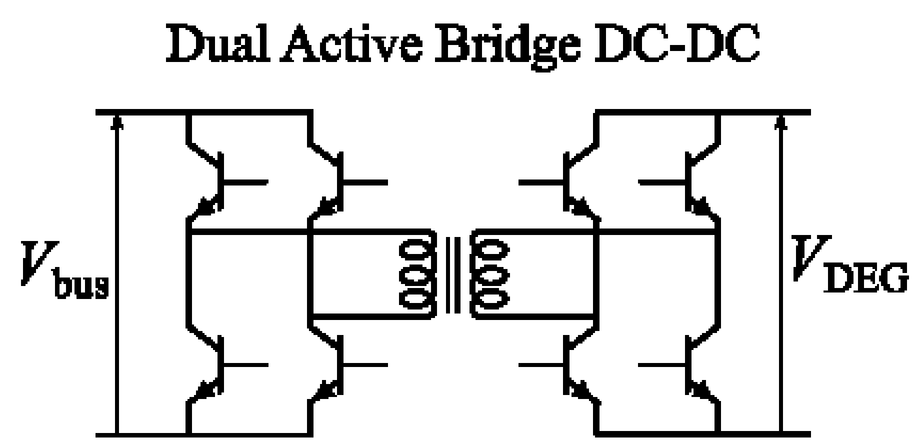
High-level control

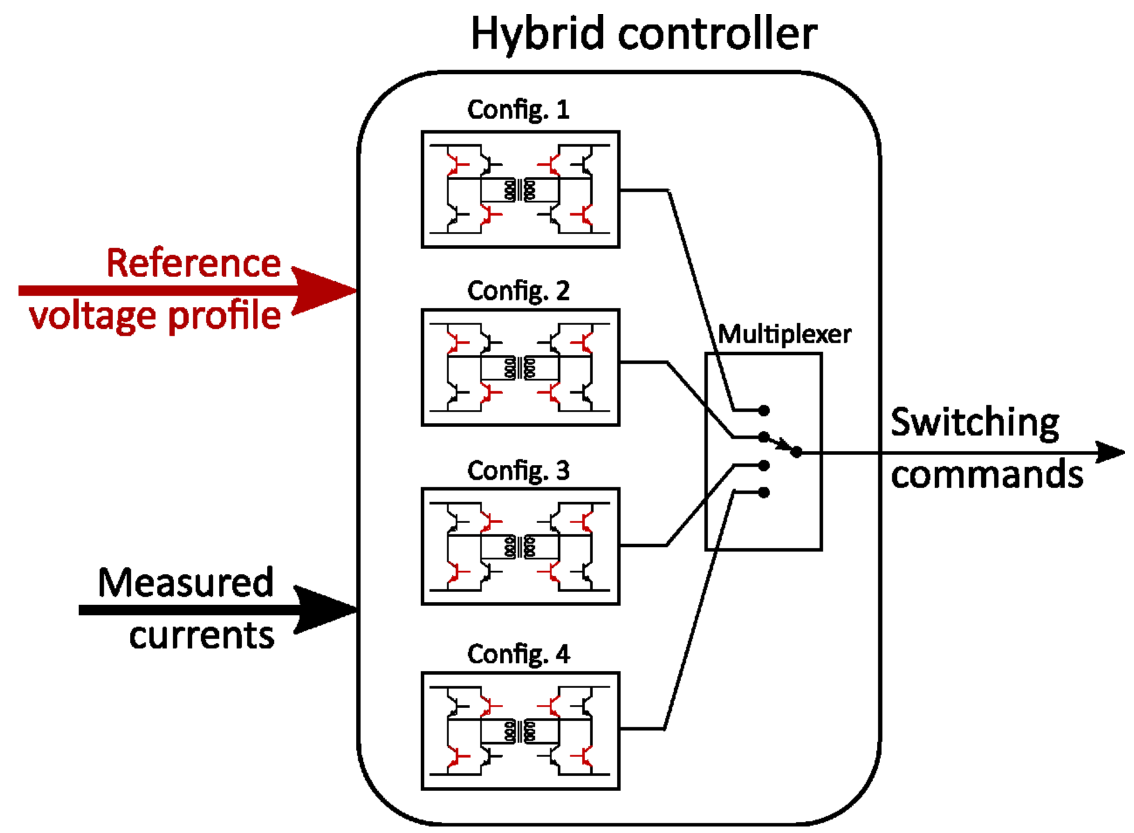


Low-level control

- Control of the Power Converter
- **Objective**: tracking pre-computed DEG voltage trajectories & maximising the power converter efficiency

Power converter: bidirectional DC-DC converter (Dual Active Bridge, DAB)





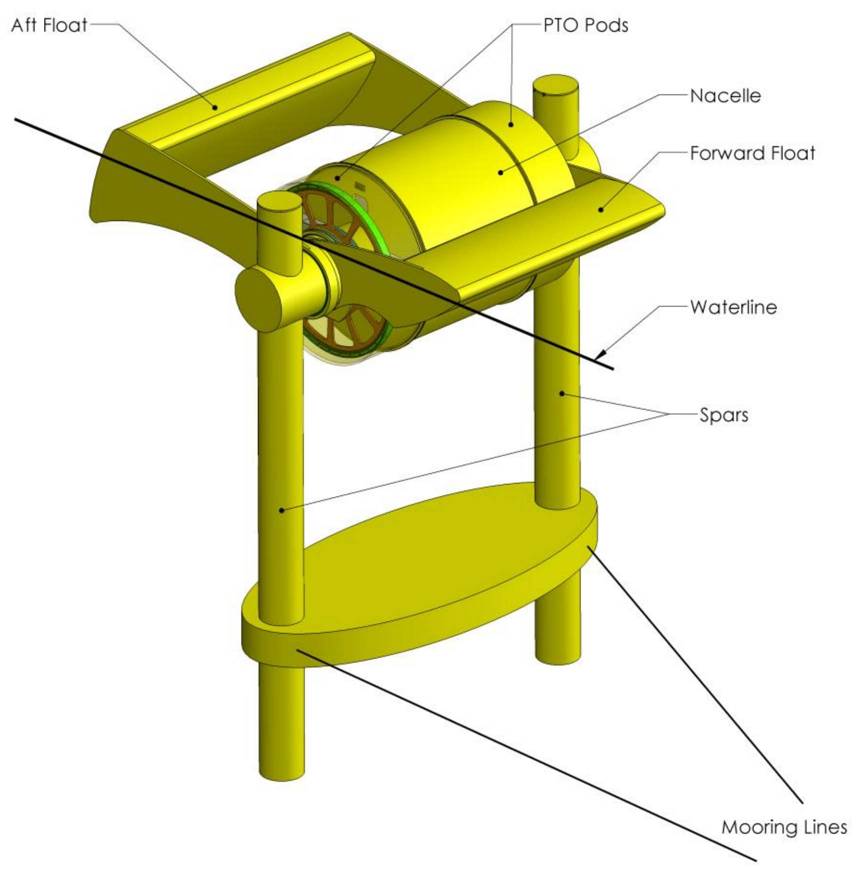
Wave Energy Advanced Control System (WEACS)

Project Lead: CPower Alba Ltd

Overview:

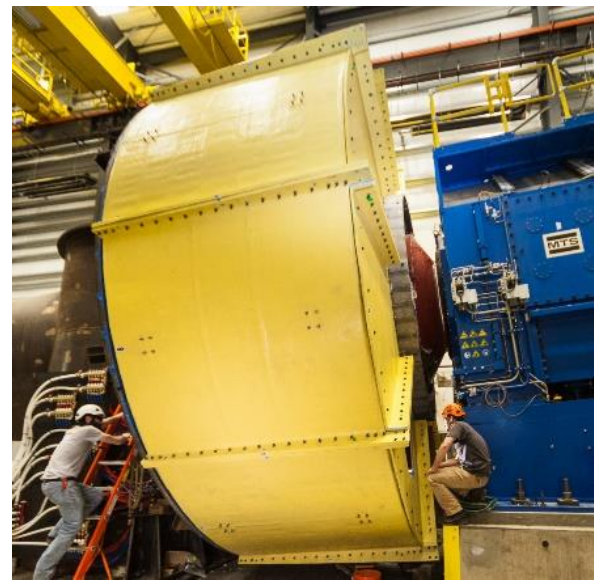
The WEACS Project effort will be directed towards the research, design and development of a control system that includes high-level supervisory and diagnostic functions, along with low-level, real-time dynamic-control processes. WEACS will serve as the central nervous system for a wave energy conversion device and will be connected to all systems within the device. Stage 1 will demonstrate the overall feasibility and expected benefits of WEACS to enable design and development to proceed in Stage 2 and testing in Stage 3.

This Project will expand on work already completed by CPower Alba, who is developing the StingRAY wave power device for utility-scale markets. The WEACS team also includes SgurrControl, who are control systems experts, and Wave Venture, a specialist wave energy consultancy and software provider. Cruz Atcheson is providing consulting services for CPower Alba and parent Columbia Power Technologies.



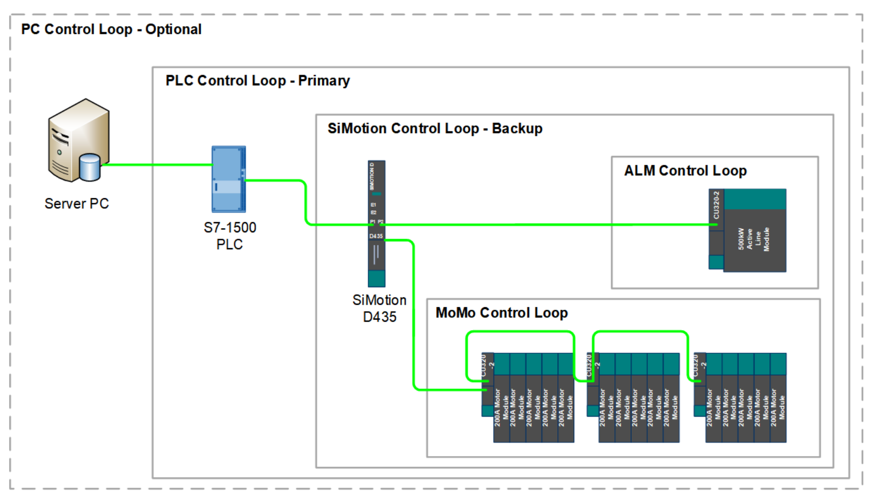
Project WEC:

StingRAY v3.2

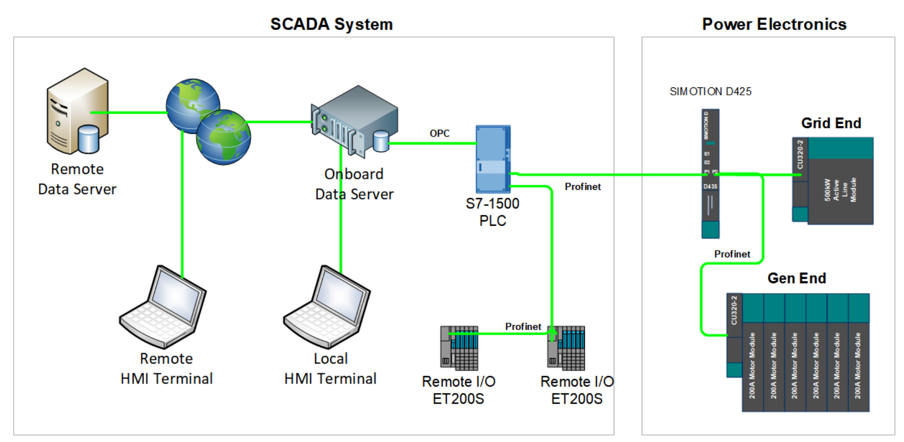


Direct-drive PTO currently being tested

SCADA Components



Control Hierarchy



Network Diagram

Project Team

Columbia Power Technologies — power from the next wave

wood.

sgurr control

WaveVenture

cruz atcheson CONSULTING ENGINEERS

Goals

The goal of the WEACS project is to significantly lower the cost of wave power through improved performance, survivability, reliability and maintainability. To achieve the Industry target of £150/MWh, a comprehensive, advanced control system is required by all wave energy device technology developers.

WEQUAD FRAME project

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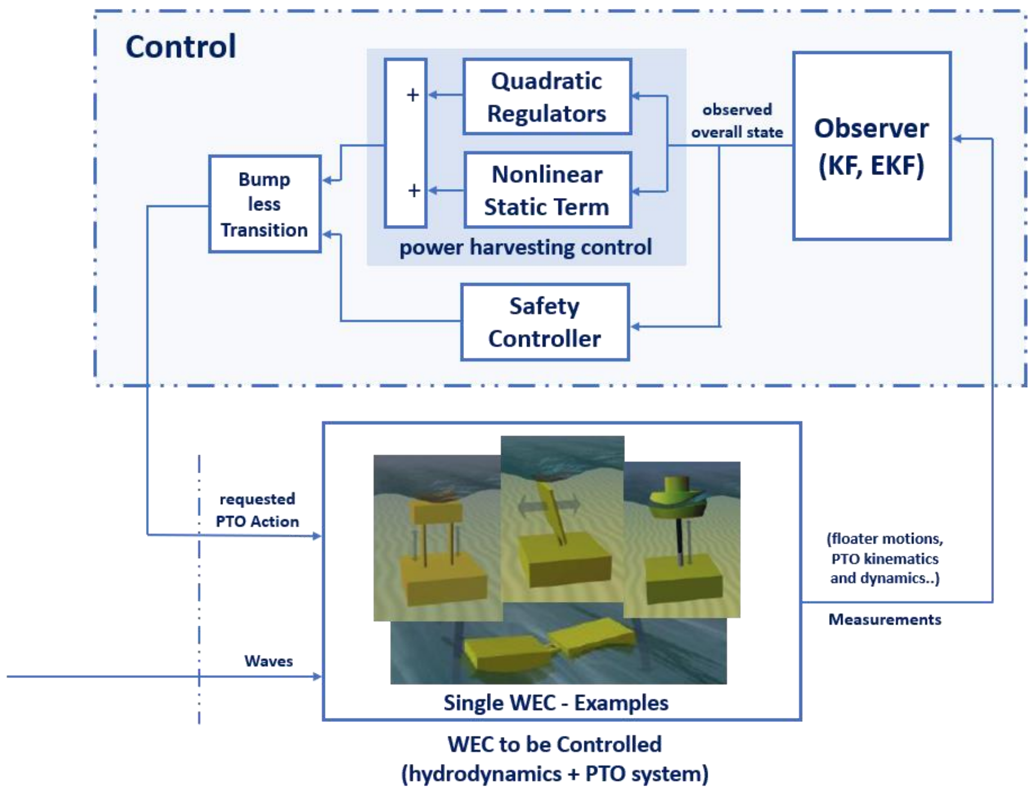
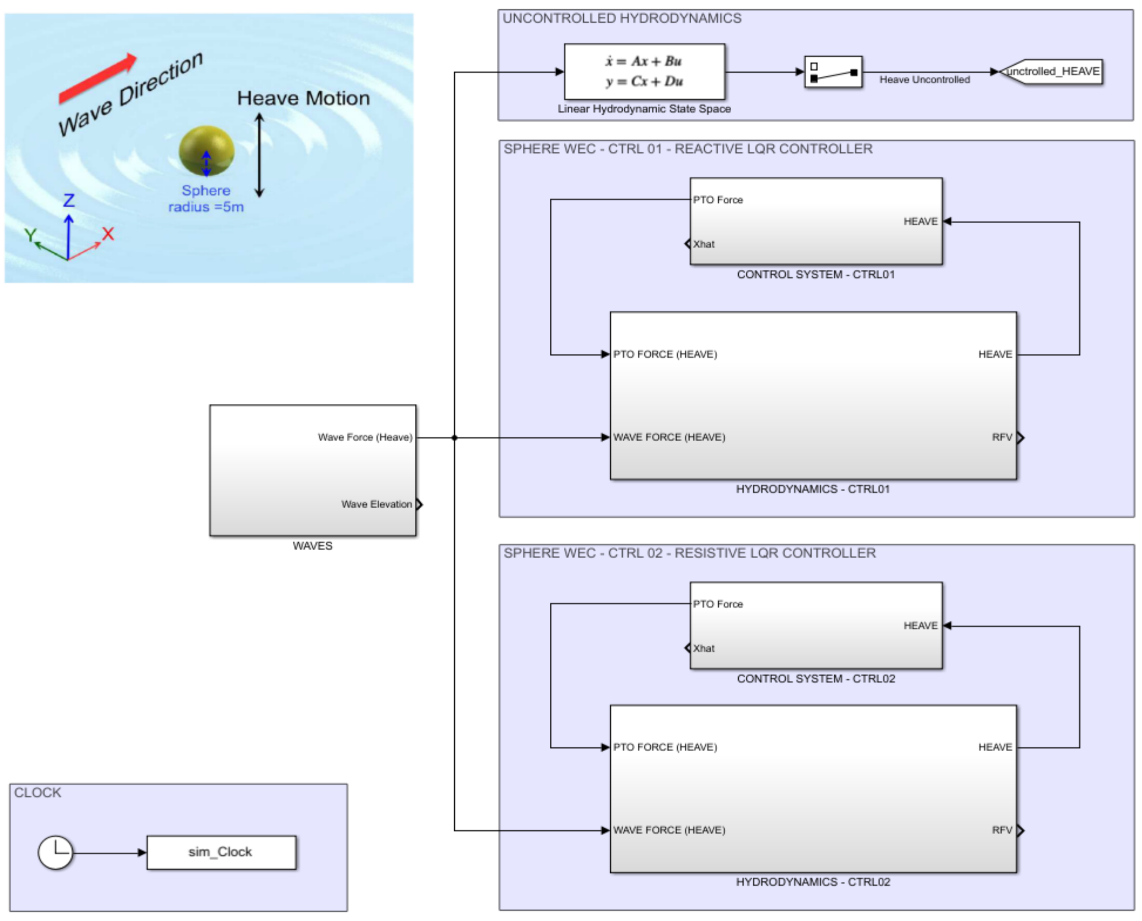
Wave **E**nergy converters linear **QUAD**ratic control **FRAME**work

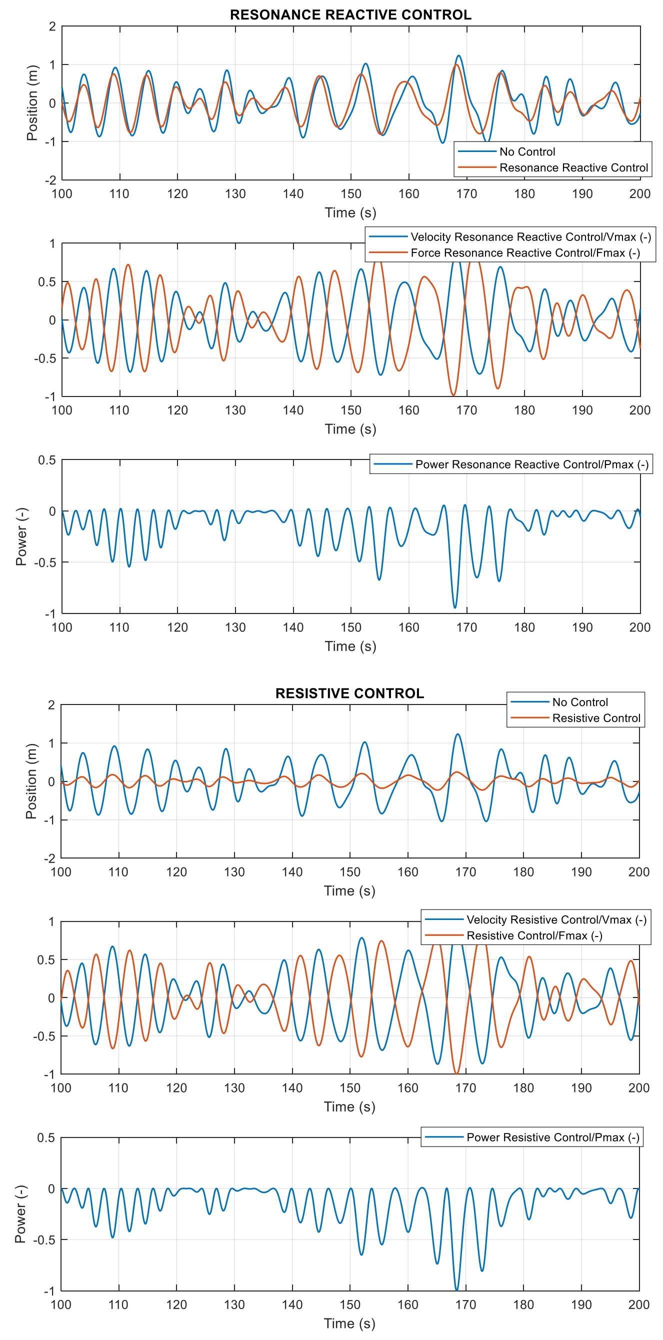
WEQUAD FRAME project main aim is to apply the linear quadratic modern control synthesis principles to multiple WEC technologies, in order to build a common control development framework for the PTOs regulating control laws.

WHAT?

Develop a model based control system architecture that can be easily fitted to every Wave Energy Converter.
The theoretical framework used as basis for the development is linear model based control theory and Kalman filtering for observation. Nonlinear ad-hoc developed terms to simplifying the synthesis procedure and create robust controllers.







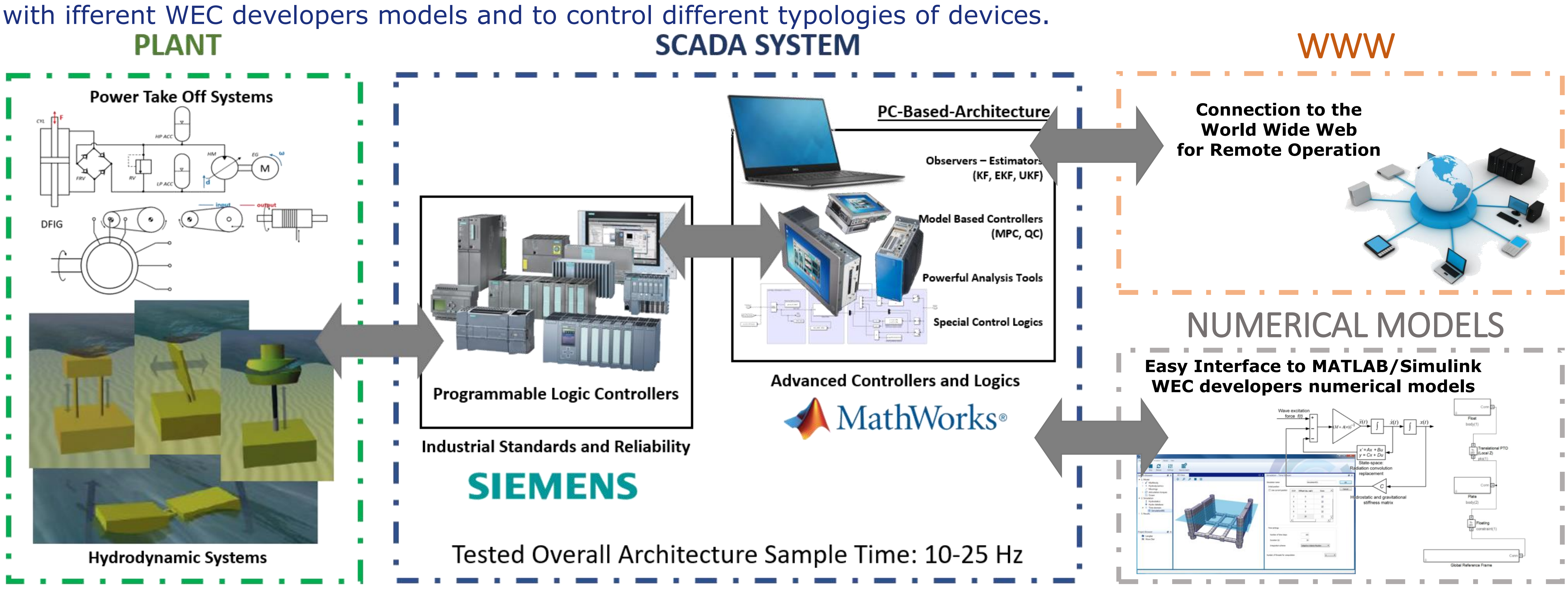
Project Power Harvesting Strategies:

- *Pure Resistive Controller*
- *Reactive Controller Resonant with Incoming Wave State*

Both for oscillating and rotating PTOs

HOW?

Using the best technologies on the market, interfacing the MATLAB/Simulink modelling and developing environment with SIEMENS Programmable Logic Controllers. Developing a computer-based flexible architecture, being able to interface with ifferent WEC developers models and to control different typologies of devices.



Project ForeWave objectives: From onboard observation to a wave forcing estimation.

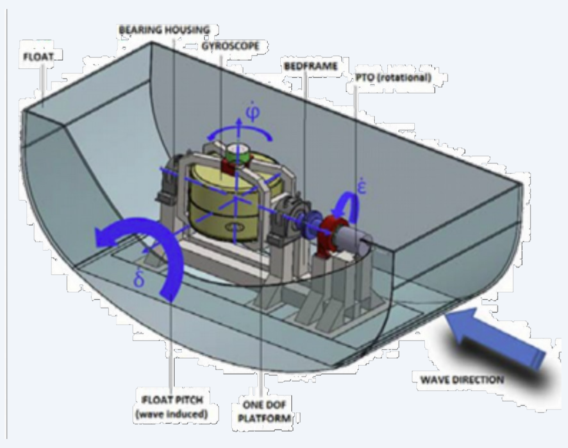
- Provide inputs for slow WEC control on a sea state by sea state basis independently of forecast;
- Provide short term wave forcing for wave by wave control based on onboard estimation.

Method 1: sea state estimation through DoF independent from PTO

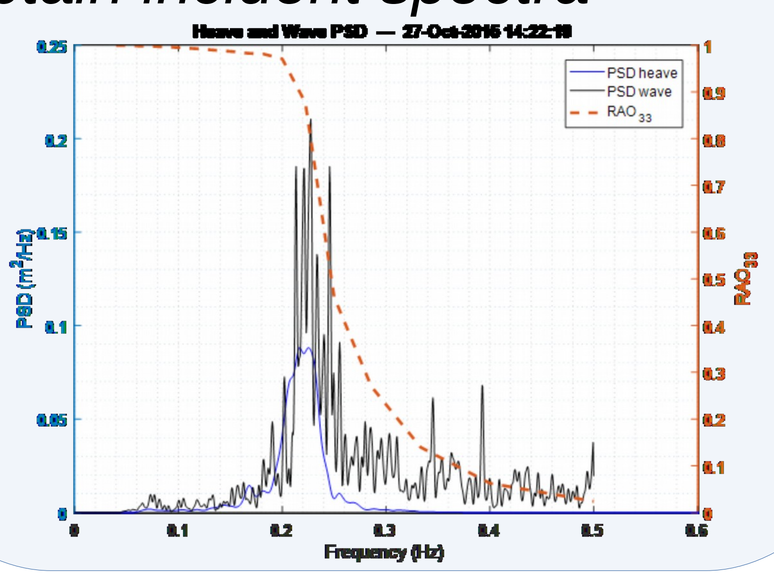
- Based on ISWEC real observation at sea.
- Uses the modelled heave RAO to estimate incident Sea state

From sensors in:

Using hydrodynamic model



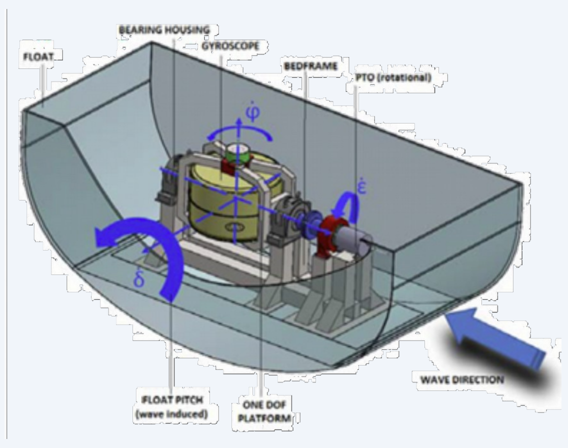
Obtain incident spectra



Method 2: sea state estimation onboard observation

- Based on ISWEC real observation at sea.
- Stage 1 feasibility uses simulation results.
- Establish statistical model between onboard observation and incident sea state parameters

From hydrodynamic model



Using multi-linear regression model

Obtain incident sea state parameters

$$T_e \quad H_s \quad \nu$$

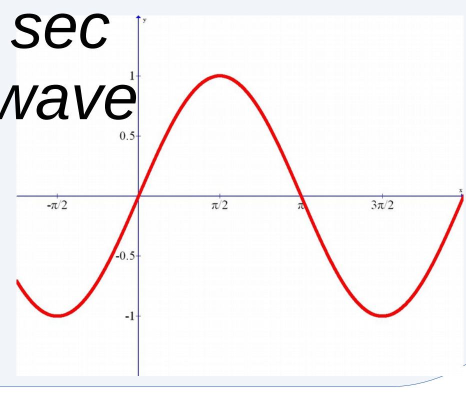
Method 3: short wave forcing from onboard observation

- Based on ISWEC real observation at sea.
- Algorithm developped by Polito.
- Implementation into CompactRIO emuator by ISC
- 10-15 sec wave forcing prediction target

From sensors in:

Through implementation in

Obtain 10-15 sec prediction on wave forcing



ForeWave ENABLES advanced WEC control strategies

Moving forward:

- explore the impact of wave stationary assumption on method 1 and 2
- Expand all methods to WECs, testing feasibility and implementation.
- Collaboration with downstream control strategy from ForeWave inputs

Nonlinear Optimal Control: Concepts, Practicalities and Benefits

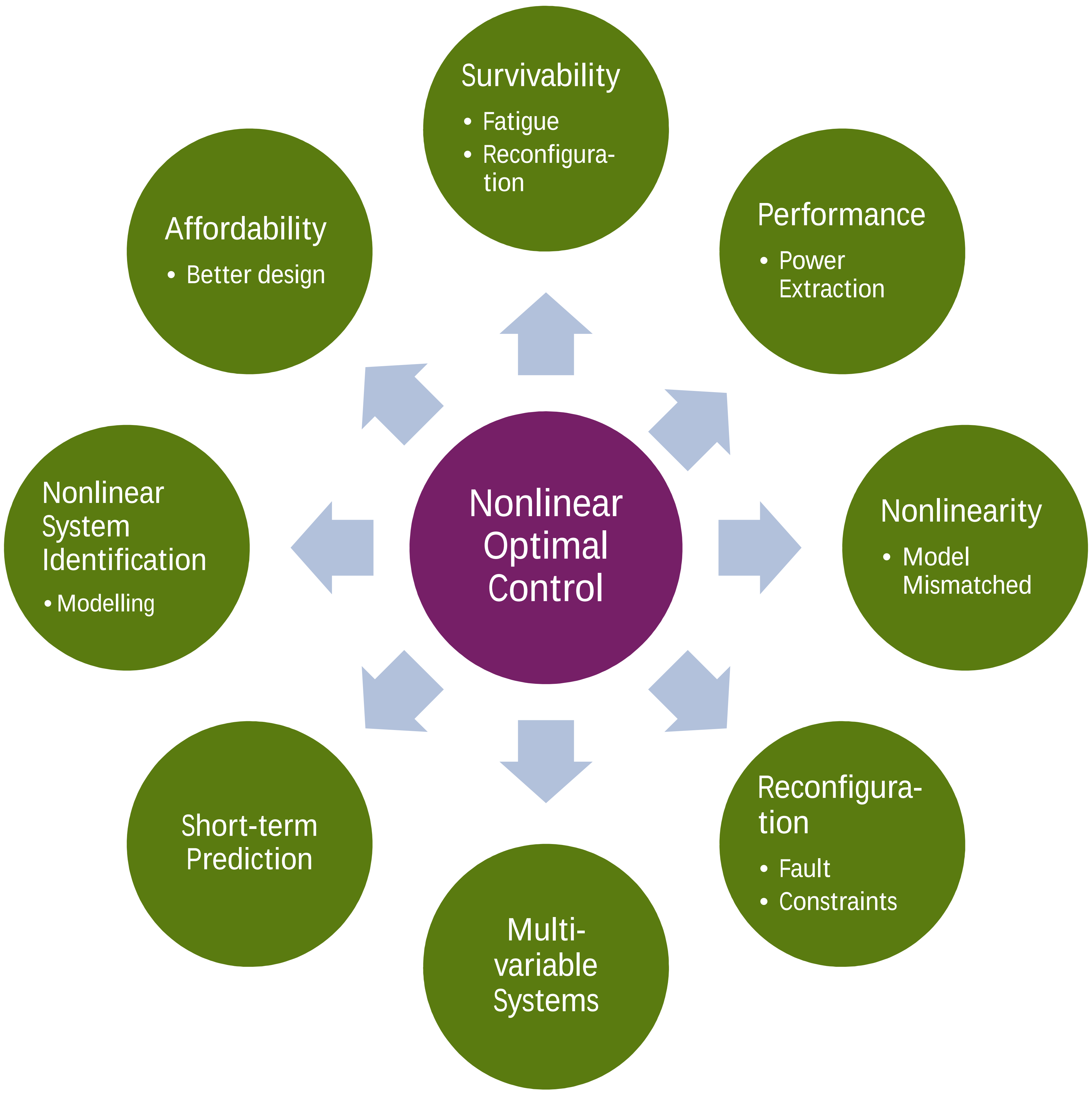
industrial systems and control

The low-level controllers within a wave energy device regulate the transfer of energy from the wave induced motions of the Wave Energy Converter (WEC), through the Power Take-Off (PTO) subsystems and ultimately onto the electrical grid. The performance of the control is therefore central to extracting as much of the available power as possible over the widest range of sea-states, and at the same time ensuring long term survivability in extreme conditions.

This project will demonstrate the feasibility of using nonlinear optimal control methods that have been gaining maturity in other industries (automotive, wind) in the application of wave energy devices. A simplified WEC/PTO simulation will be used to evaluate and quantify the potential of nonlinear optimal control and its modelling and sensing requirements, including:

- optimising in real-time a true nonlinear problem to maximise power extraction and at the same time maximising survivability;
- practical issues, such as robustness, implementation and model derivation.

ISC is the project lead and our project partners are Mocean Energy and Pelagic Innovation Ltd.



ISC is also project partner to two other WES projects, namely:

1. ForeWave (Stage 1), with INNOSEA Ltd – To demonstrate how a WEC can be used to estimate the current wave state and to predict wave forcing actions in the future. ISC is involved in the real-time hardware implementation .
2. Mocean WEC (Stage 2), with Mocean Energy Ltd – This WES project is developing the design of a Novel WEC. ISC is involved in the development of control system and also the control system FEED design.

ISC Ltd is a highly specialised control consultancy company based in Glasgow. We are the leading control engineering consultancy in the NI Alliance Partner Network in Scotland. We specialise in:

- Real-time control implementation, data logging/data acquisition systems and signal processing systems using NI software and hardware.
- Troubleshooting poorly performing control systems.
- Enhanced/Advanced control assessments and recommendations for control improvements through loop tuning and actuator upgrades.
- Research and development studies to assess design options early in the development phase, for example designs with advanced control theory and estimate performance.

Two of our projects with Houlders won the NI Graphical System Design Achievement awards in 2012 and 2013.

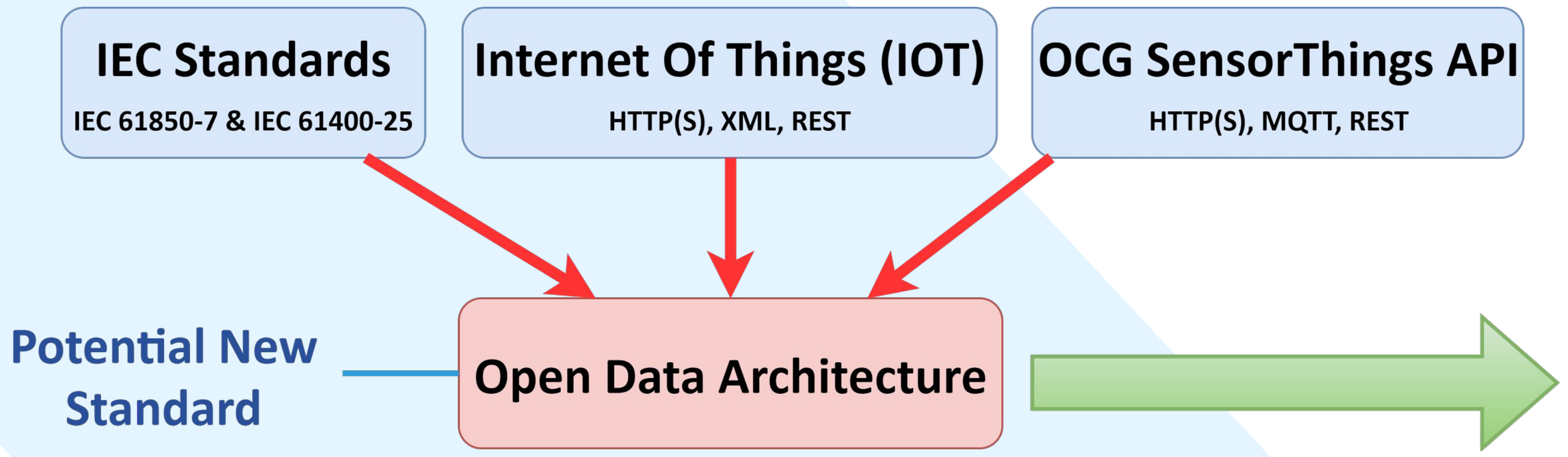
• GRAPHICAL SYSTEM DESIGN • ACHIEVEMENT AWARDS — Advanced Control Systems – WINNER

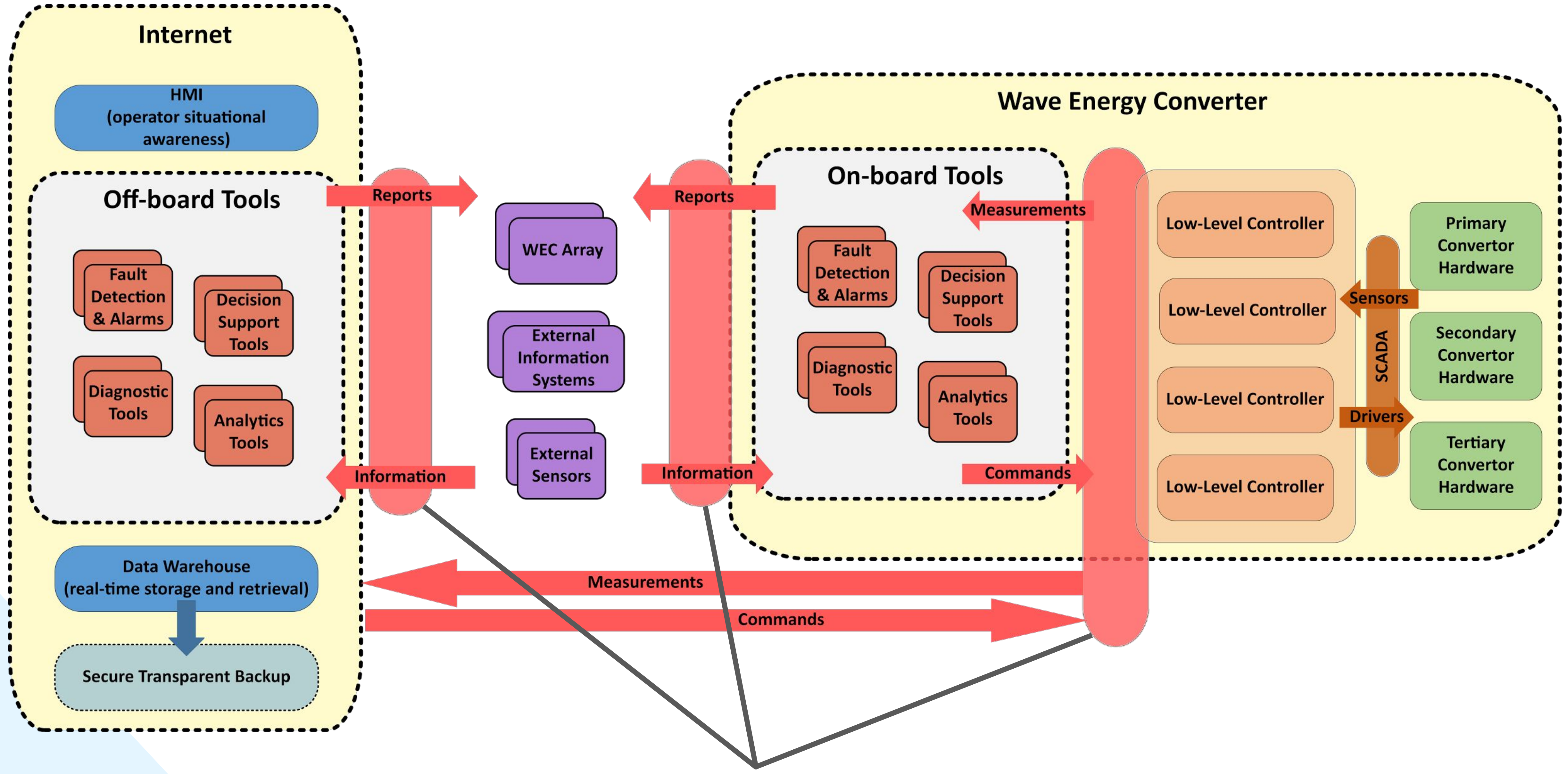
NATIONAL INSTRUMENTS Alliance Partner

• GRAPHICAL SYSTEM DESIGN • ACHIEVEMENT AWARDS — APPLICATION OF THE YEAR AWARD

DataWave

An Open WEC Data Architecture for Supervisory Control & Smart Data Analytics





Using a Standard Open Data Architecture (ODA) for Wave Energy Converter (WEC):

- Defines **common syntax and semantics** by providing:
  - Definitions and naming standards.
  - Data formatting and storage rules.
  - Data transport guidelines.
- Encourages **communication between devices**, internal and external.
- Optimal for allowing **automation and control**.
- **Easy to process** information for monitoring.

Open Data Architecture - DataWave

Facilitate communication between components and systems.

DataWave - Open Data Architecture:

- Using input from **existing technologies and standards**.
- An Open Data Architecture is a **key enabling technology**
- Adoption of a WEC Open Data Architecture:
  - facilitates **common, reusable tools** for **data management, trends and predictions** on longer-time horizons than the immediate current sensed parameters are possible.
- Introduces **modularity** to WEC system and sub-components
  - Standard is capable of being used per WEC or even between components.
  - Allows for introducing and changing components with **minimal interface changes and minimal integration effort**.
- Allows creation of onboard and offboard Tools to provide functions such as:
  - **Diagnostic Processes**
  - **Alarm Systems**
  - **Decision Support**
  - **Operator Situation Awareness tools**
- Open standard means any vendor can develop tools - not locked into a particular vendor.

CEORL

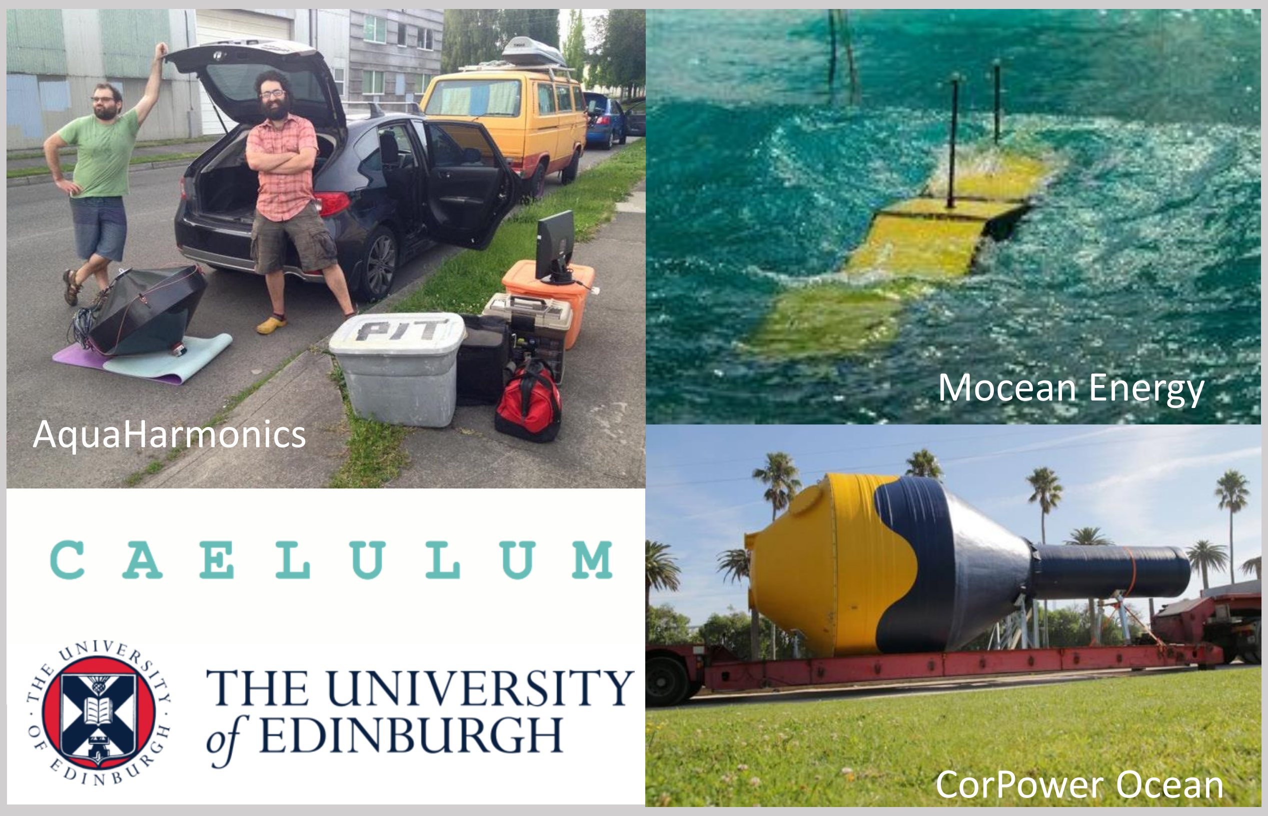
Cost of Energy Optimised by Reinforcement Learning

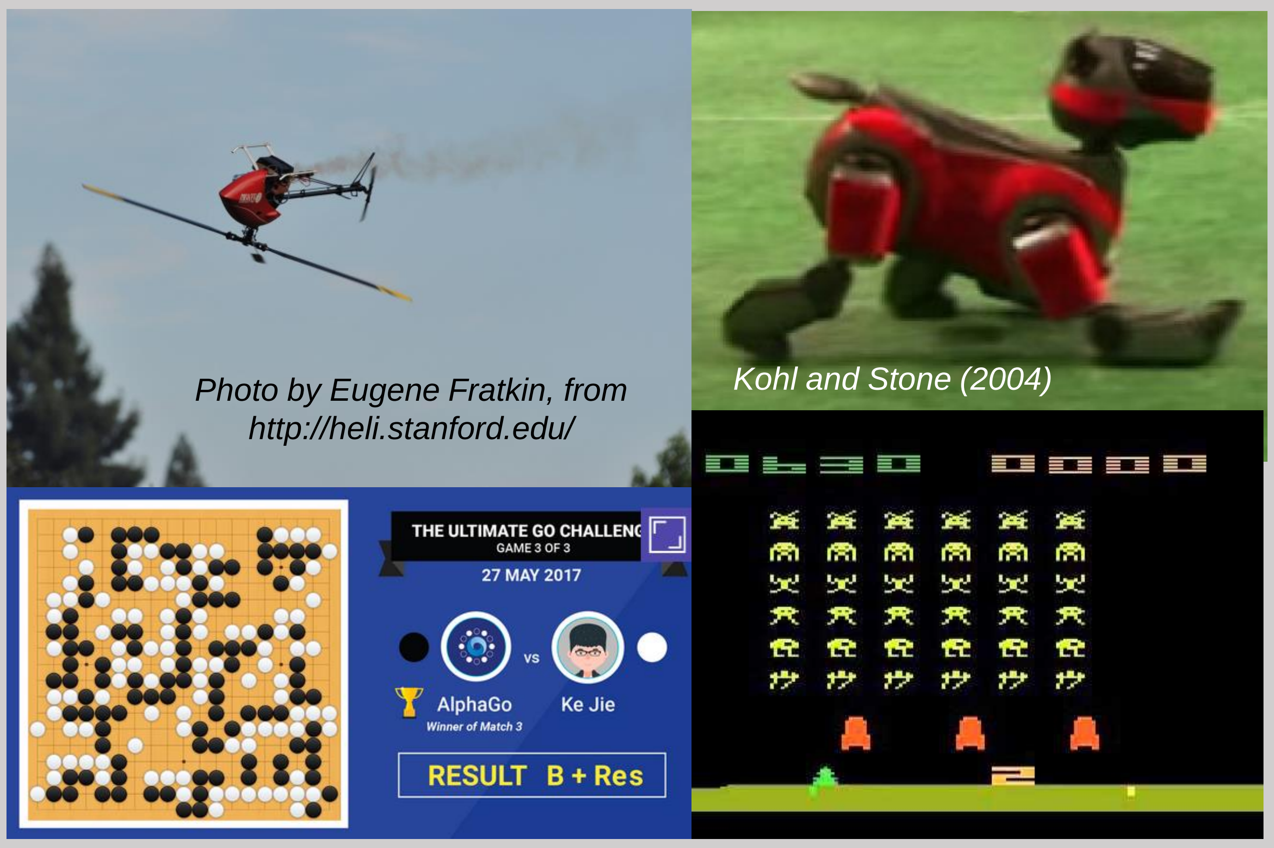
Consortium: Paul Stansell (MaxSim Ltd), Alexandra Price (Wave Conundrums Consulting), Alex Hagmüller and Max Ginsburg (AquaHarmonics Inc)

Partners: Max Carcas (Caelulum), David Pizer, David Forehand (The University of Edinburgh), Mocean Energy, CorPower Ocean

RL Application Examples

- Training helicopter stunt control
  - Pre-trained on simulation to prevent costly crashes
  - Agent learns dynamic control from experience
- AlphaGo (DeepMind) beat human Go world champion
  - More permutations than atoms in the universe
  - Requires sacrificial moves for long term gains
- Leaning to play Atari 2600 games
  - Inputs- pixels on screen only; Reward – game score / lives.
  - Same Q-learning algorithm learnt a controller for all 49 games.
- Sony Aibo: 3 hours of learning - faster than existing gaits





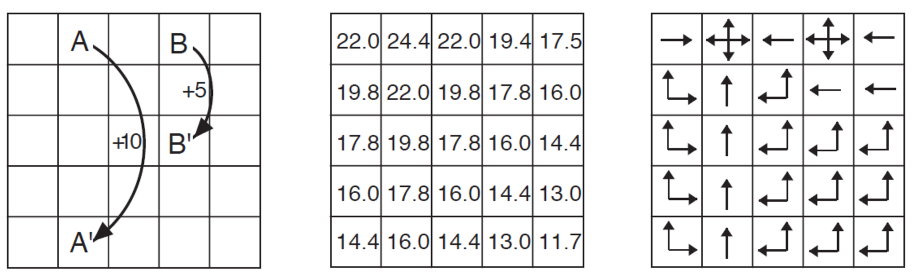
WEC Control Challenges

- Model-based control:
  - Only as effective as the model
  - Specific to device type & individual machine
  - A human needs to understand the dynamics & mechanisms
- Sea-state specific control
  - Spectrum requires 0.5-2hrs data; always represents the past
  - Changes can be fast due to tidal interaction
- Optimising power capture not best for LCoE:
  - WEP metric included power capture and maximum loads
  - Investors require performance and reliability targets to be met

RL Learning: Gridworld

In the gridworld each square is a state. Actions are up/down/left/right. The agent receives reward -1 if moving to any state apart from A/B, which gives rewards +10/+5 and jumps to state A'/B'. Iterating the equation computes value function V for each state. From V we compute the optimal action in each state. The set of states with their optimal actions is the optimal policy (π_*).

$$V(S_t) \leftarrow V(S_t) + \alpha\Big[R_{t+1} + \gamma V(S_{t+1}) - V(S_t)\Big]$$

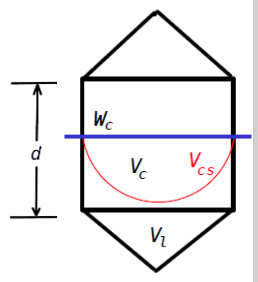


22.0	24.4	22.0	19.4	17.5
19.8	22.0	19.8	17.8	16.0
17.8	19.8	17.8	16.0	14.4
16.0	17.8	16.0	14.4	13.0
14.4	16.0	14.4	13.0	11.7

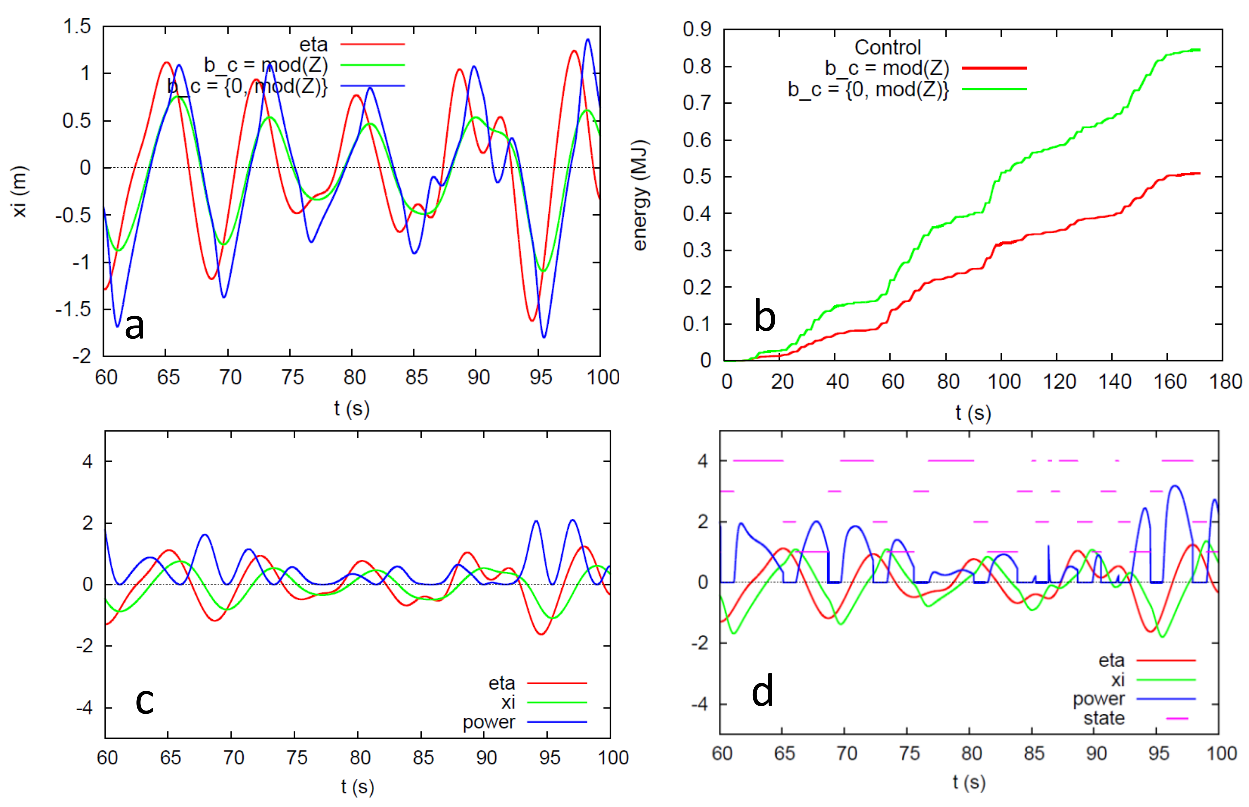
Gridworld v_* π_*

Early Investigations (Stansell)

- Simple heaving model (d= 2m):
  - Approximate non-linear hydrodynamics
  - Mass-spring-damper
- Benchmark: b = mod (Z)
  - Analytical optimum for real unconstrained problem
- Reinforcement Learning: b = {0, mod(Z)}
  - ε-soft on-policy Monte Carlo RL algorithm
  - 4 states: depend on sign of velocity and wave elevation slope
  - Return (power capture) optimised over 16s
- Results:
  - Over 50% more power capture



state index	state description
1	$\dot{\eta} < 0,\ \xi < 0$
2	$\dot{\eta} < 0,\ \xi \geq 0$
3	$\dot{\eta} \geq 0,\ \xi < 0$
4	$\dot{\eta} \geq 0,\ \xi \geq 0$

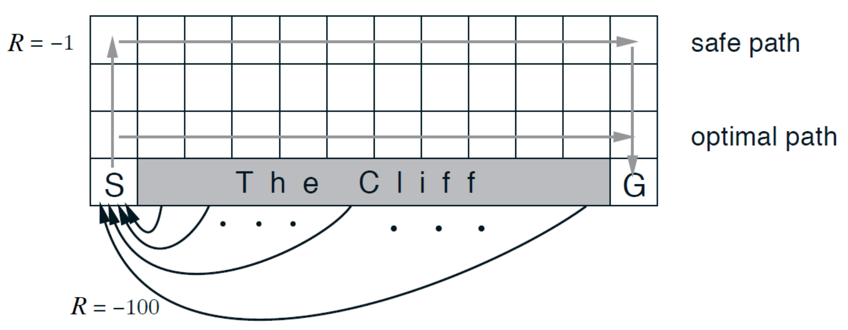


a. Wave elevation (eta), displacement for mod(Z) damping, displacement for RL.
b. Cumulative energy for mod(Z) damping and RL.
c. Wave elevation (eta), displacement (xi) and power for mod(Z) damping
d. Wave elevation (eta), displacement (xi), power and states for RL.

RL Learning: Cliff Gridworld

The Cliff gridworld has same actions as above. The agent learns to travel from S to G. Rewards are -1 if moving to any state apart from "The Cliff", which gives -100 and returns agent to S. Iterating the off-policy equation for Q computes the action-value function. From Q we compute the optimal policy. Off-policy methods (eg, Q-learning) find the "optimal path"; on-policy methods (eg, Sarsa) find the "safe path". Off-policy methods learn faster, but on-policy methods can adapt better to non-stationary environments.

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha\Big[R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t)\Big]$$



From: Sutton and Barlo, 'Reinforcement Learning: An introduction' 2017

Adaptive Hierarchical Model Predictive Control of Wave Energy Converters

Project Description:

We propose a hierarchical adaptive optimal control framework to maximise wave energy conversion efficiency while guaranteeing safe operation for a large range of sea states. The framework combines the strengths of several key promising technologies in control and wave prediction to adaptively achieve the best trade-off between energy maximisation and survivability.

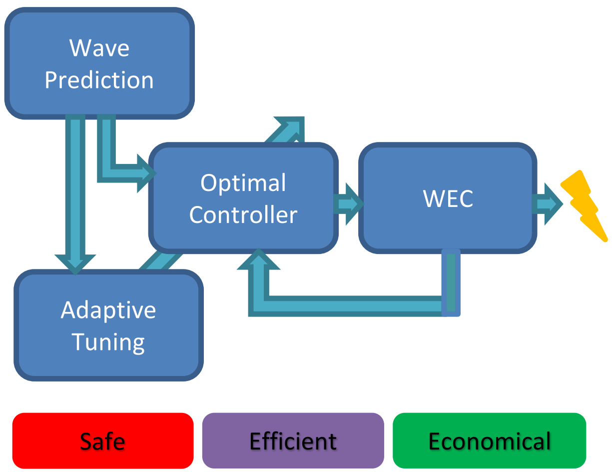


Fig.1 Illustration of the Control Framework

Highlights of our work:

- Fundamental noncausal optimal control theory have been developed for WEC control problem: maximising energy output directly. (accepted by IEEE Trans. on Control System Technology)
- Fundamental adaptive control theory for WEC control problem has been developed to handle modelling uncertainties and disturbances. (papers in submission)
- Fast nonlinear optimal control algorithms for coping with complicated WEC system described by high-order model with nonlinearities and subject to constraints for safe operation has been developed (International Journal of Control, 2017).
- Convex model predictive control has been developed for WEC control to directly maximise energy output (Renewable Energy, 2014) and more efficient MPC algorithms are being developed.
- Deterministic Sea Wave Prediction Algorithms have been developed into a more mature stage after the recent sea trial tests.

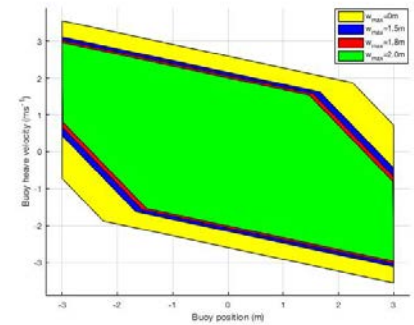


Fig. 2. The safe operation region can be determined according to the maximal incoming wave magnitude.

The Team:

- **Dr Guang Li** (Queen Mary Univ. of London) is a lecturer in Control Systems. His current projects (as PI) relevant to control problems in marine engineering and wave energy include “Control of Launch and Recovery in Enhanced Sea-States” (£373K, EPSRC), “Control of Floating Wave Energy Converters with Mooring Systems” (£111K, Advanced Newton Fellowship, the Royal Society), “Fast Adaptive Optimal Control with Application to Sustainable Energy Systems” (£12K, the Royal Society). He has pioneered several key control technologies for WEC systems.
- **Prof Michael Belmont** (Univ. of Exeter) leads the systems engineering aspects of marine renewable energy at SuperGen, Exeter. He pioneered the discipline of Deterministic Sea Wave Prediction, (DSWP), which offers large reductions in installed capacity costs for wave energy capture devices. Recent funding highlights are: A sole science provider in a €9M EU demonstrator project for full scale use of DSWP for enhanced marine energy capture in OPT Ltd’s Power Buoy, PI on a £1.1M EPSRC Grand Challenges project: Very Large Scale Tidal Stream Farm Optimisation, PI on the £677K EPSRC project: Dynamic environment prediction: safe launch and recovery in high sea states.
- **Prof Chris Edwards** (Univ. of Exeter) holds a chair in Control Engineering. He has over 350 refereed papers and is the co-author of two text books on sliding mode control. He is PI on many projects founded by EPSRC and EU etc.
- **Dr Cameron McNatt** (Mocean Energy) has key expertise in computational modelling for marine and wave energy applications.
- **Dr Chris Retzler** (Mocean Energy) has key expertise in experimental physics and wave energy, with specific experience in the provision of control and PTO for WEC scale models.

Correspondence: Dr Guang Li, Queen Mary University of London. Email: g.li@qmul.ac.uk Tel: +44(0)20 7882 6116

IMPACT Project

Adam Stock[1], Robert Clayton[1], Joao Cruz[2], Yannick Debruyne[2]
Wood[1], Cruz Atcheson[2]

cruz atcheson CONSULTING ENGINEERS

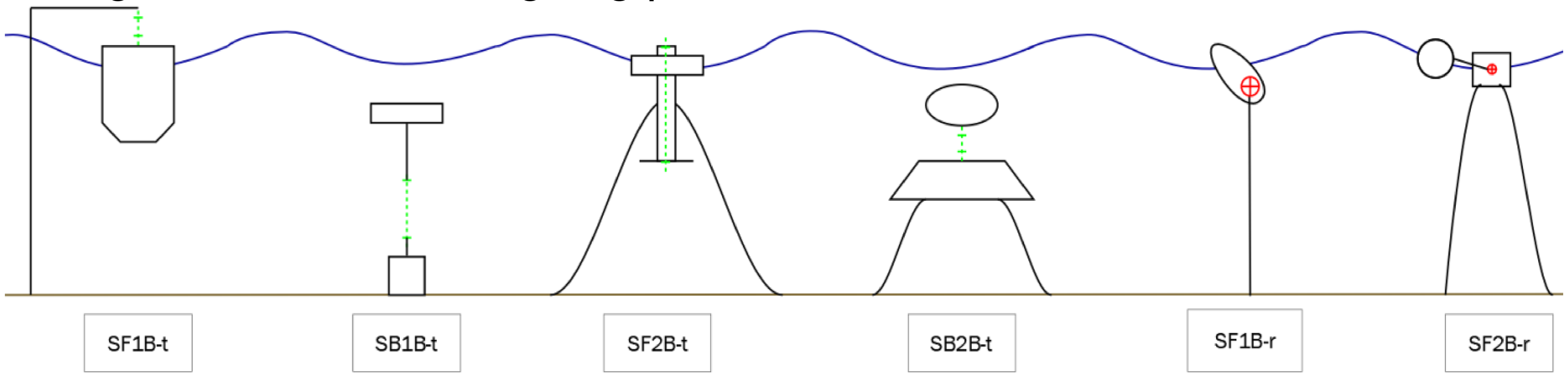
wood.

Integrated Marine Point Absorber Control Tool

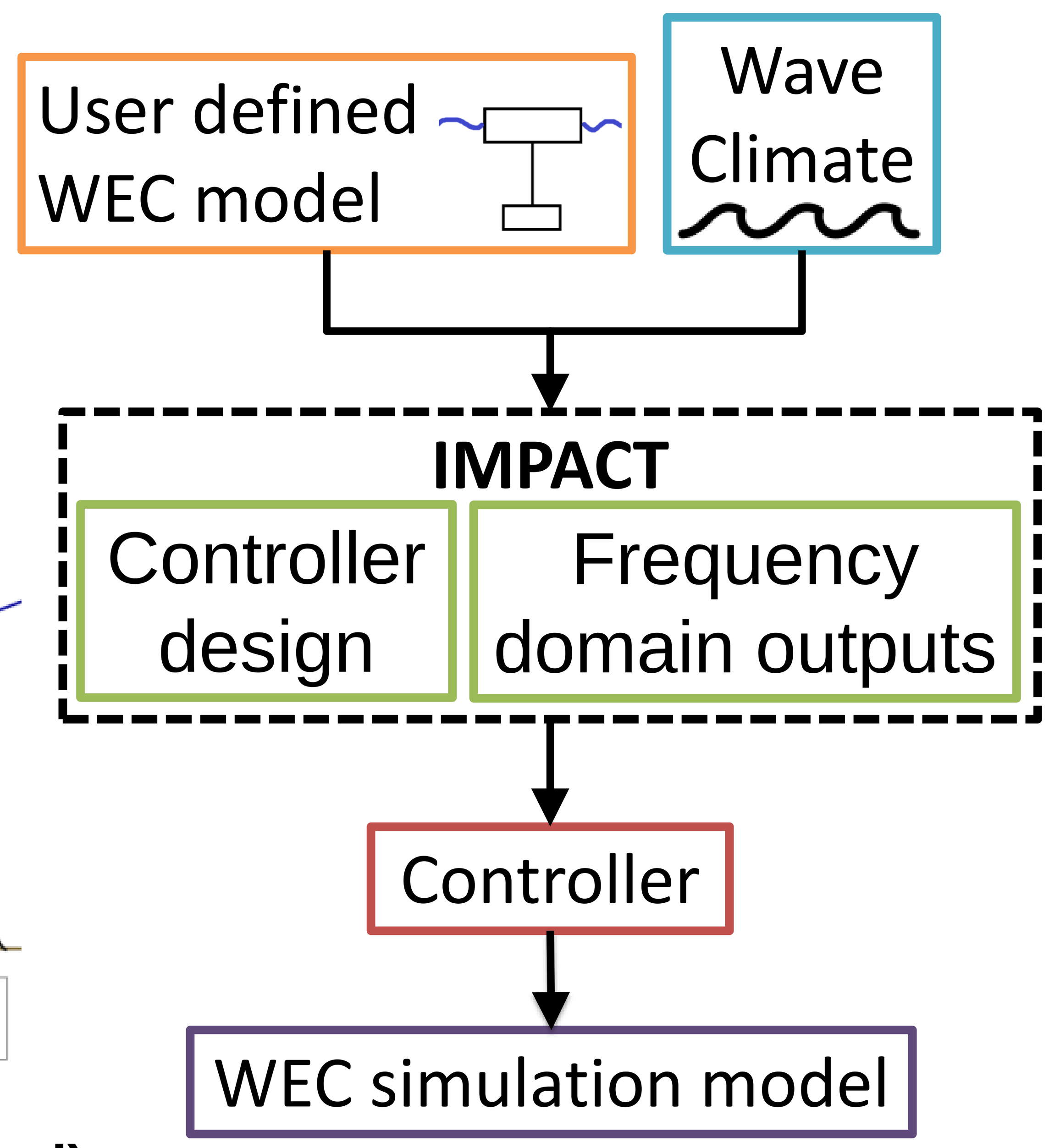
- Aims to develop a **generic tool** for designing point absorber controllers.
- Designed as a MATLAB toolbox to provide users with a **simple to use interface** whereby the key variables associated with their point absorber can be defined.
- Using the key variables, the tool will be able to **build a control model** of the WEC.
- IMPACT then helps the user to **define the control regime** for the Wave Energy Convertor (WEC) that is **stable** and gives the required **dynamic response**, taking into account **the whole system.**
- With the controller designed, it can then be exported and tested in a suitable WEC simulation model such as **MATLAB Simulink**.
- The **tool will be generic** and can therefore be used for the majority of point absorber developers. The tool aims to allow controller design to be sped up and for it to be undertaken **in conjunction with the WEC design.**

IMPACT Functionality

IMPACT's end goal aims at producing an appropriate controller design following the definition of key WEC design and wave resource parameters. The outputs of IMPACT can be used in further controlled WEC simulation models. In Stage 1, the project builds upon a characterisation of point absorber WECs and Power Take-Off subsystems. Model databases are created to support the development of a generic tool for designing point absorber controllers.



Characterisation of wave point absorbers types
(SF=surface, SB=submerged, 1B=1 Body, 2B=2 Bodies, t=translational, r=rotational)



Project Consortium Details

Wood
With over 25 years' experience in renewables, Wood's control engineering team specialises in the development of innovative and effective control systems for wind and tidal turbines. They work with a variety of renewable device manufacturers, including key industry leaders and innovators within all areas related to control design.

Cruz Atcheson (CA)
CA is an independent engineering consultancy active in the offshore renewable energy industry. CA's team of technical experts have experience working with over 30 WEC developers globally. The team have been at the forefront of developing and implementing design tools and methodologies to support the development of WEC.

Come and speak to us or Tweet @Woodplc
Email: Adam.Stock@Woodplc.com

wave energy SCOTLAND

Wave Energy Scotland
Annual Conference 2017

Weetics

Wave Energy Enhancement Through Innovative Control System

Stage 1 – Feasibility studies

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Introduction

Despite the significant achievements in the last decades, wave energy devices are still at an earlier stage of development than other offshore renewable energy technologies. Unfortunately, an issue **normally relegated to the last phases of development** is the design of global control architectures and supervisory systems.

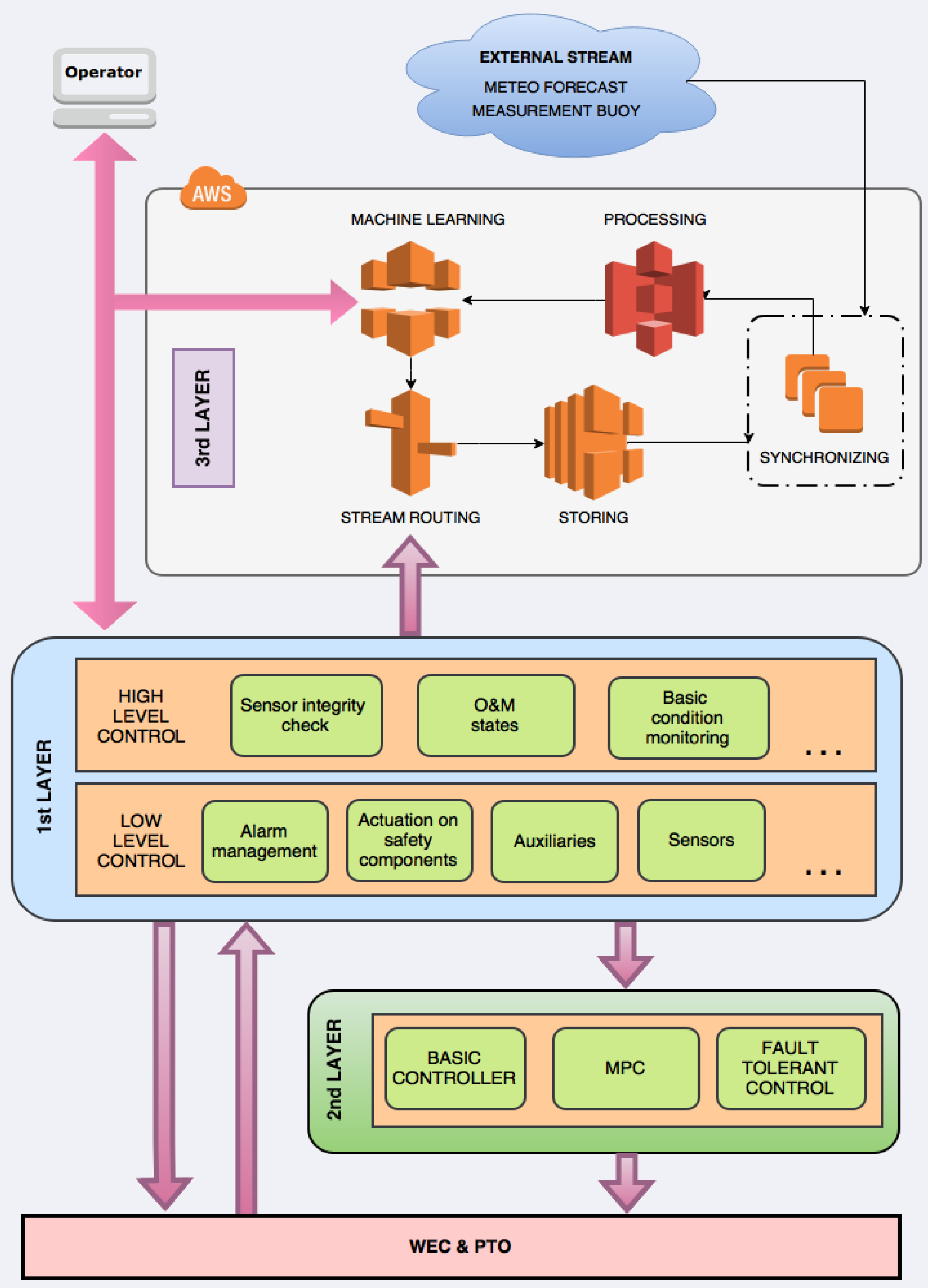
In order to give response to this need, WEETICS proposes a **multilayer control architecture** aiming at evaluating the best control action according to both internal and external criteria. The Control System (CS) framework is a **global solution applicable to different WECs** since it considers the device as a whole system where each block encapsulates specific control functions.

The 1st stage of the project **assesses the requirements** of this novel control system methodology, its **applicability** to different WECs and PTOs typologies and **readiness** of the project to proceed to Stage 2 [1].

Overview of the Control System Framework

The proposed CS structured in three layers, each one with a clearly defined goal.

- **Layer 1:** responsible of the safe and reliable operation of the WEC.
- **Layer 2:** exclusively dedicated to the optimisation of WEC power production.
- **Layer 3:** is the true innovation of the CS as it oversees device survivability, reliability and performance in light to improving system affordability using data fusion and machine learning performed via cloud-hosted applications.



Work plan

In order to achieve this objective, a work plan structured in three work packages is proposed. The work plan involves the following types of activities:

- **WP1: Definition of the control strategy.** It will describe the proposed CS framework and overall architecture, the links between its components, and the specific requirements regarding measuring and sensing, modelling and prediction, processes and algorithms, as well as control commands and actions to be taken.
- **WP2: Demonstration of feasibility.** It will assess the expected improvement in the WES Target Outcome Metrics, the technology readiness to provide the required functions and applicability of to specific WECs and PTOs.
- **WP3: Project management.** Overall management, communication and coordination between the different partners, monitoring of the technical progress of the project, management of the risks and establishment of contingency plans.

Control System Functions and Requirements

Layer 1 – Integrated Control System. The 1st layer is the **main control program** implemented in the WEC Programmable Logic Controller (PLC). It centralises every monitored data from all WEC sub-systems. This layer is also responsible of guaranteeing the output data stream containing data and status of sensors that will enable both system monitoring in a local station, but most importantly, to an external database processed in the 3rd Layer.

Functionality	Measurements, signals and sensors	Process & control commands
Protect staff safety, integrity of plant assets and the environment	• Heat and fire presence • Gas and fume spreading • Water intrusion and fluid leakage • Device amplitude and accelerations • WEC position monitoring • Staff presence	• Default in sensor or communication • Fault detection and diagnostic • Assign the operational state (Ready, O&M, Storm protection)
Safe power production of plant	• Pressure, temperature and humidity • Temperature of critical components • Generator rotational speed • Vibration monitoring of the PTO • Position of safety components • Over-voltage/current	• Safe WEC operation • Real time controller decision for Layer 2
Basic condition monitoring	• Pressure sensors • Temperature sensors • Humidity and dew-point sensor • Speed/position encoder • Position switches • Current and voltage sensors	• Ageing • Automated maintenance • Sensor integrity check

Layer 2 – Real Time Controller. The 2nd layer of the control system architecture is exclusively dedicated to the **WEC power production**. In fact, there are three real time core controllers and an algorithm that enables power smoothing assuming the WEC is equipped with an energy storage system.

Functionality	Modelling and prediction	
Basic controller	• Accurate Wave-to-Wire (W2W) model • Sea state dependent resistive control • Adaptive resistive control	• Management of the Energy Storage System
Model Predictive Control (MPC)	• Accurate wave excitation force prediction • MPC model including W2W • Latching and PTO damping control • Synchronisation of the control action	
Fault Tolerant Control (FTC)	• Reconfiguration of operational bounds • Use of redundant PTO parts • Watch fault recovery	

Layer 3 – Data Fusion and Machine Learning. The 3rd layer represents an organised collection of physic-based models and methods of data integration and advanced analytics hosted in a **cloud-base service**. It is used to feedback information into lower levels of the WEC control. The PLC should support high-level communication protocols for data exchange with Layer 3, a robust ICT infrastructure should guarantee network performance and availability.

Functionality	Modelling and prediction	
Integrity check	• Detects malfunction of sensor • Detects anomaly in auxiliary system	• Data routing and synchronization • Integration with external data streams (WMI, meteo forecast, onshore substation, O&M planner)
Power performance improvement	• Digital WEC model: performance simulation and modelling actualization • Machine learning	
Advanced condition monitoring	• Ability to compute long term effects • Machine learning	

Future work

- **Stage 1: Feasibility and Project Definition (01/2018)**. Complete the feasibility study of the CS methodology, perform the risk analysis, and fully scope Stage 2 activities.
- **Stage 2: Design & Development (2018).** Develop the CS methodology in a simulated environment and quantify benefits (WES Target Outcome Metrics). Investigate the requirements for physical implementation in existing laboratory testing, or in a demonstrator WEC/PTO for Stage 3. Preliminary practical implementation in a controlled environment.
- **Stage 3: Control System Demonstration (2019).** Implement the CS using production software and physical demonstration in a prototype (NWEC/PTO call, others).

References

[1] *WEETICS_D1 Definition of the control system methodology_v1.0, Tecnalia and Oceantec, Nov. 2017.*

Predictability-bounded Control of the Mocean WEC

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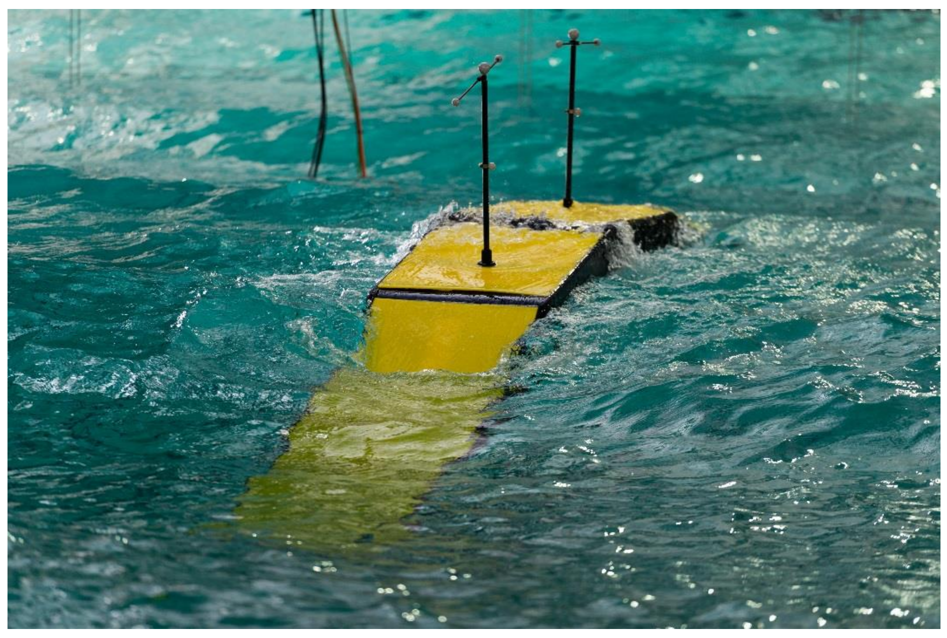
PROJECT OVERVIEW

This project investigates the feasibility of applying an adaptive control methodology to the Mocean Wave Energy Converter in conjunction with a fully electrical rotary Power Take Off system. The control strategy employs predictability analysis and online nonlinear modelling to maximise usable control bandwidth within irregular seas whilst disregarding frequency components with low estimation certainty. In this way the performance of the controller is not adversely affected by poor sea state or system model estimation as would be the case for most optimal controllers. This approach has several practical advantages:

- **Very low computational overhead compared to other non-linear model structures.**
- **Inherent adaptation as the plant changes due to bio-fouling, ageing or damage.**
- **Applicability to all WEC/PTO systems including non-linearities such as dead zones, friction and rate limits.**
- **Accommodation of physical constraints e.g. position limits, PTO torque limits and uni-directional power flow.**

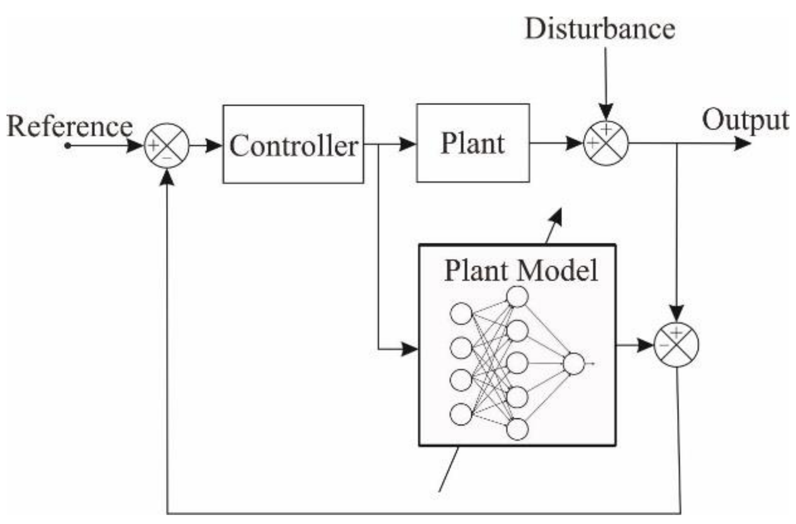
WEC

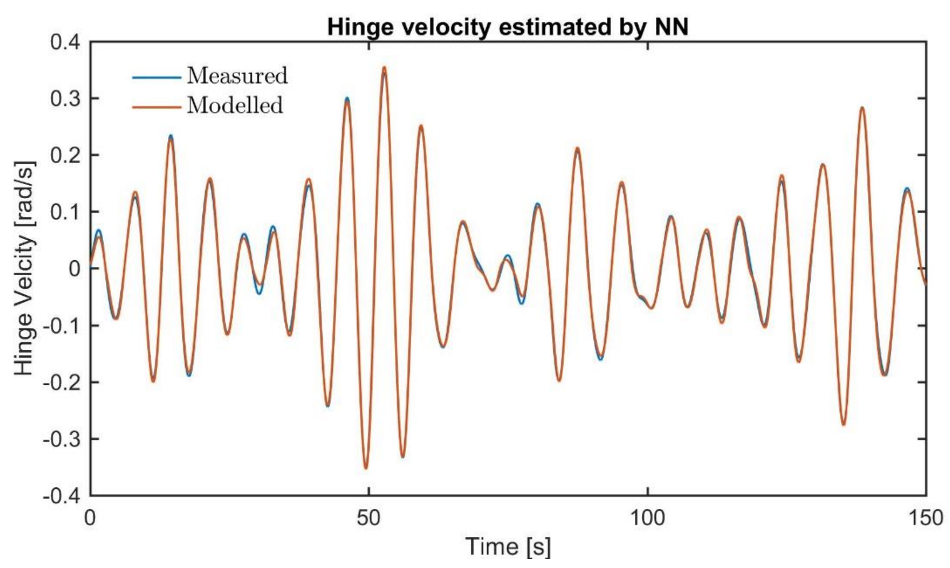
The Mocean WEC is a hinged raft with two bodies connected by a single revolute joint. Wave forcing and the bodies' dynamic responses cause a relative motion about the hinge. A rotational PTO at the hinge transforms the kinetic energy into electricity. Currently Mocean are in a WES Stage 2 NWEC project. In this project we are considering a full scale model of the WEC with a fully electrical rotary Power Take Off system.

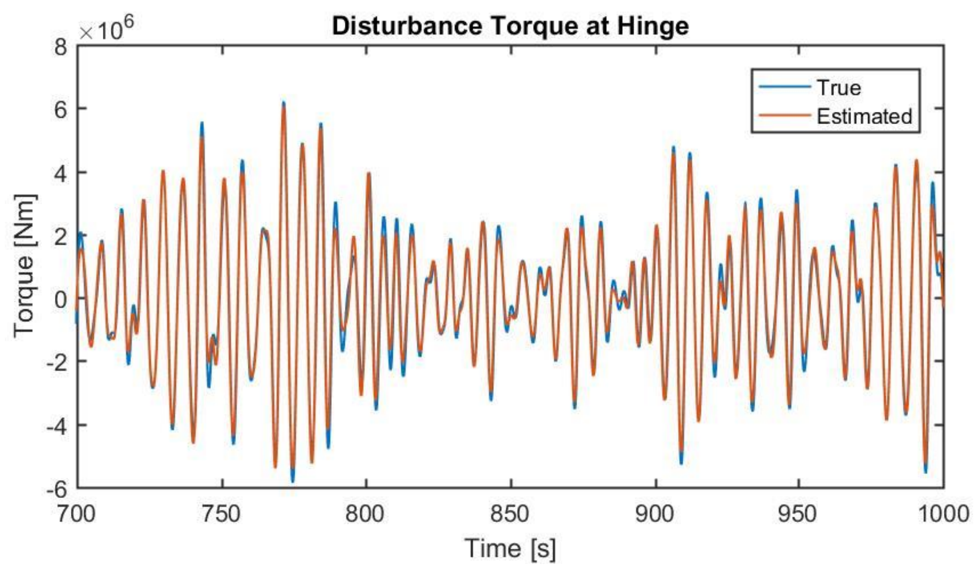


ON-LINE SYSTEM MODELLING

A WEC is highly nonlinear and intended for long deployment times, so the accuracy of a traditional model-based controller could be compromised. The proposed strategy overcomes this by adapting a Neural Network (NN) model of the WEC and PTO whilst the system is in operation. NN derived models are shown for fitting the hinge velocity and unmeasurable excitation force for the Mocean WEC in irregular seas with excellent accuracy.



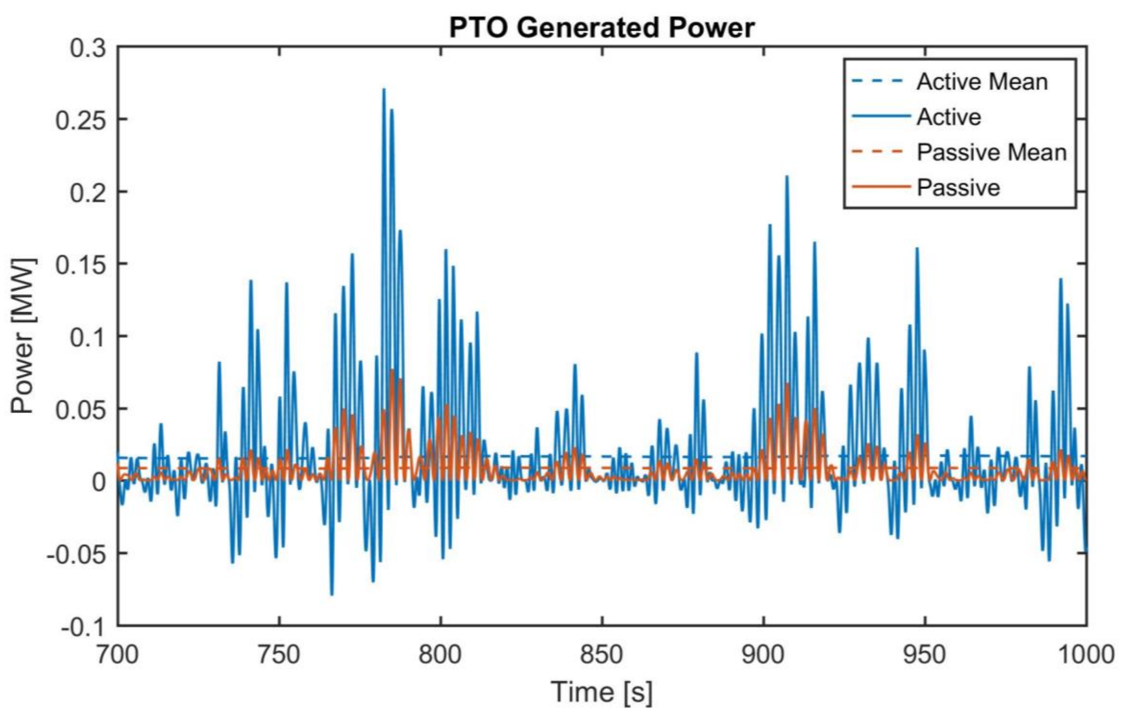


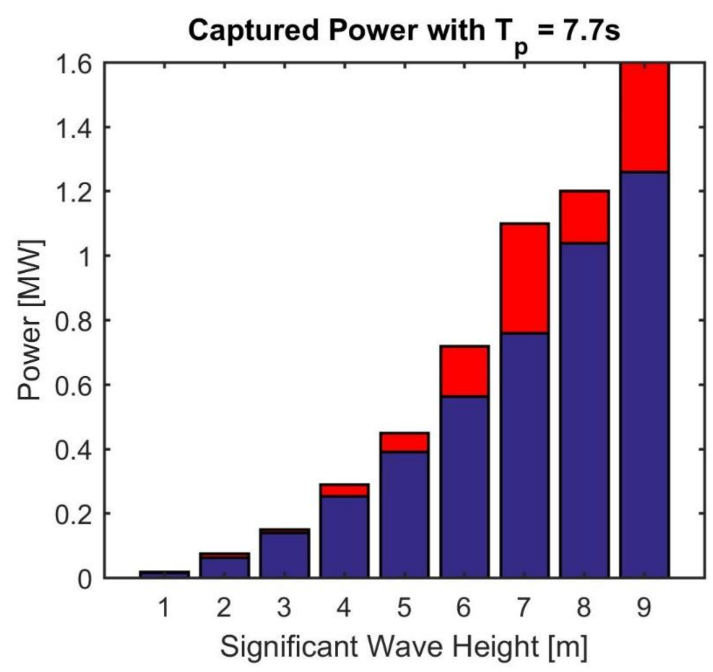


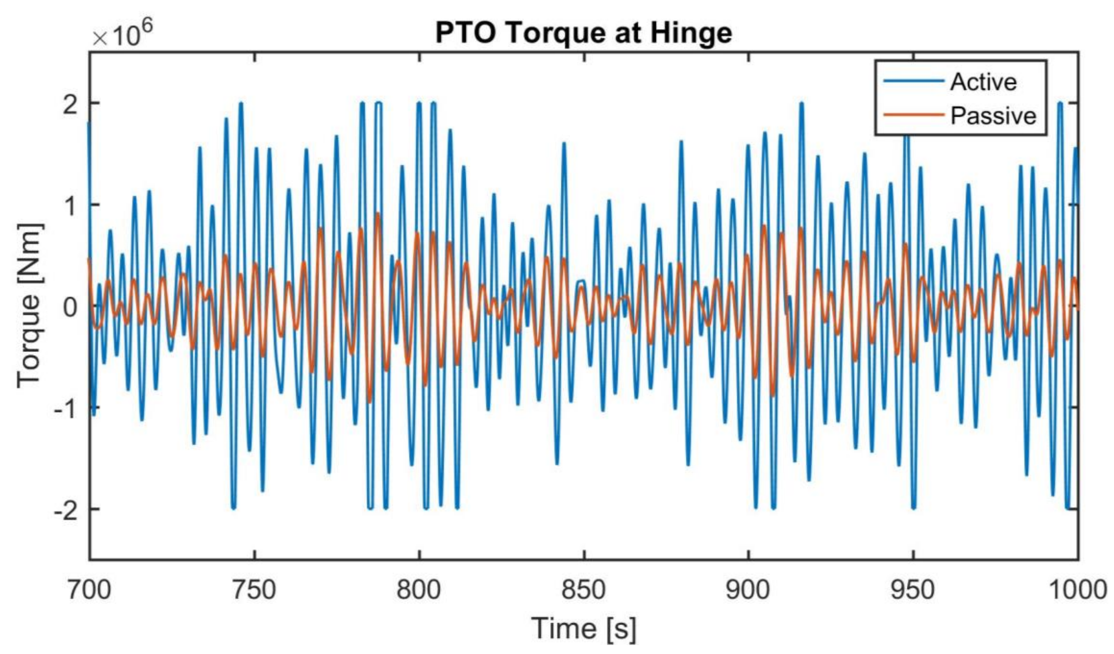
CONTROL STRATEGY

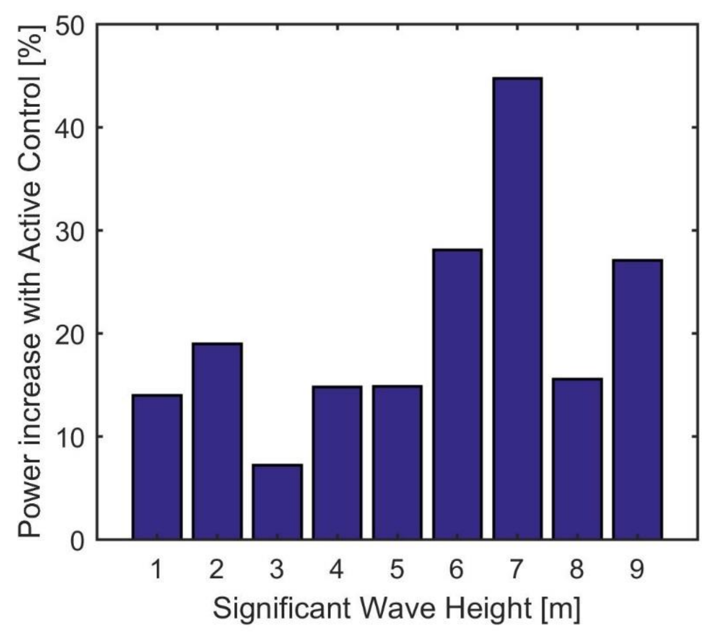
We are currently employing the Simple and Effective control strategy [Fusco 2013]. An optimal velocity trajectory is evolved from the estimated wave excitation force and the WEC hydrodynamic response. Physical constraints such as position and velocity limits are incorporated in an intuitive way. The strategy is computationally simple so readily implemented in real time and is inherently robust to parameter variation, non-linearity and damage. It is also tunable for different objectives – e.g. maximum efficiency, survivability, minimising LCOE.

Preliminary results show increases in power capture of up to 45% compared to the optimal passive damping setting with no PTO torque limit. Results are also shown for 4-Quadrant operation including a 2MNm PTO torque limit. Results for 2-Quadrant operation show minimal performance degradation









FURTHER WORK

Full analysis of performance benefits across a wide range of sea states and model uncertainties;

Demonstration of feasibility in terms of: Reliance only upon measurable and available information, real-time implementation and operation within the PTO performance envelope.

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Adaptive Control of the WaveSub WEC using a Romax Electro-mechanical PTO

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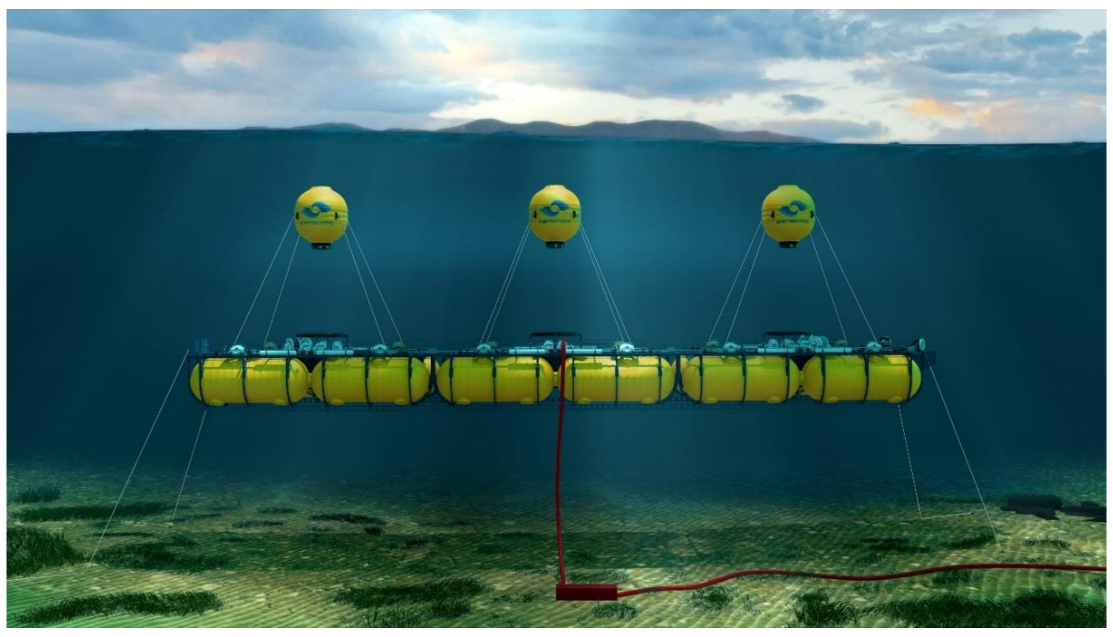
PROJECT OVERVIEW

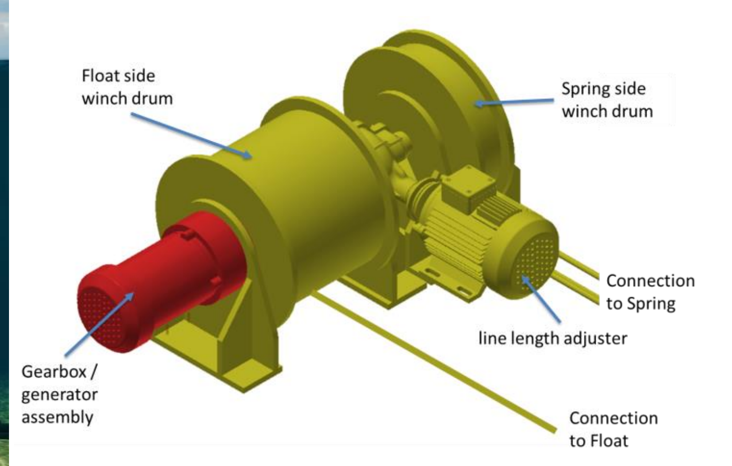
The project investigates the feasibility of applying an adaptive control methodology to the WaveSub Wave Energy Converter (WEC) in conjunction with the Romax electro-mechanical Power Take Off (PTO) system. The two systems are, in principle, compatible and well suited to provide an efficient and cost-effective overall solution. The proposed control methodology is computationally simple and can accommodate physical constraints such as position limits in a simple and robust manner. It also requires no *a priori* knowledge of plant dynamics. This offers several advantages over other strategies as:

- **Implementation is very straightforward.**
- **It is insensitive to errors in estimates of the plant (sensors, PTO and WEC), which are not always easy or even possible to achieve.**
- **It is robust to parameter variation and nonlinearity (e.g. plant ageing or damage), and fault tolerant.**
- **It is applicable to any WEC/PTO system combination without the need for extensive retuning.**

MARINE POWER SYSTEMS WAVESUB WEC

WaveSub is a submersed point absorber with unique multi-tether configuration and variable geometry which can be tuned to the prevailing sea state. A float moves with the waves and reacts against a moored base. The tethers pull on rotational drums which are attached to a PTO. WaveSub has geometric controllability also – the float-reactor separation is adjustable for mean sea state tuning and survivability.





ADAPTIVE CONTROL STRATEGY

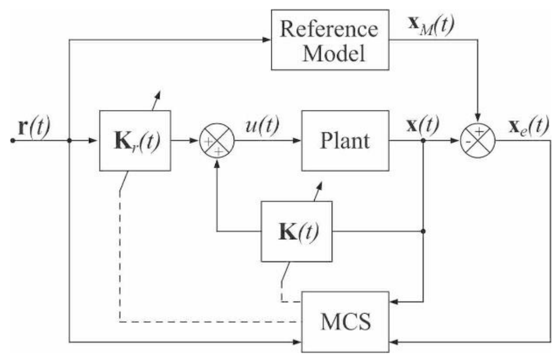
The Simple and Effective control strategy [Fusco 2013] is used here. An optimal velocity trajectory is evolved from the estimated wave excitation force and the WEC hydrodynamic response. The strategy is computationally simple so readily implemented in real time and is inherently robust to parameter variation, non-linearity and damage. It is also tunable for different objectives – e.g. maximum efficiency, survivability, minimising LCOE.

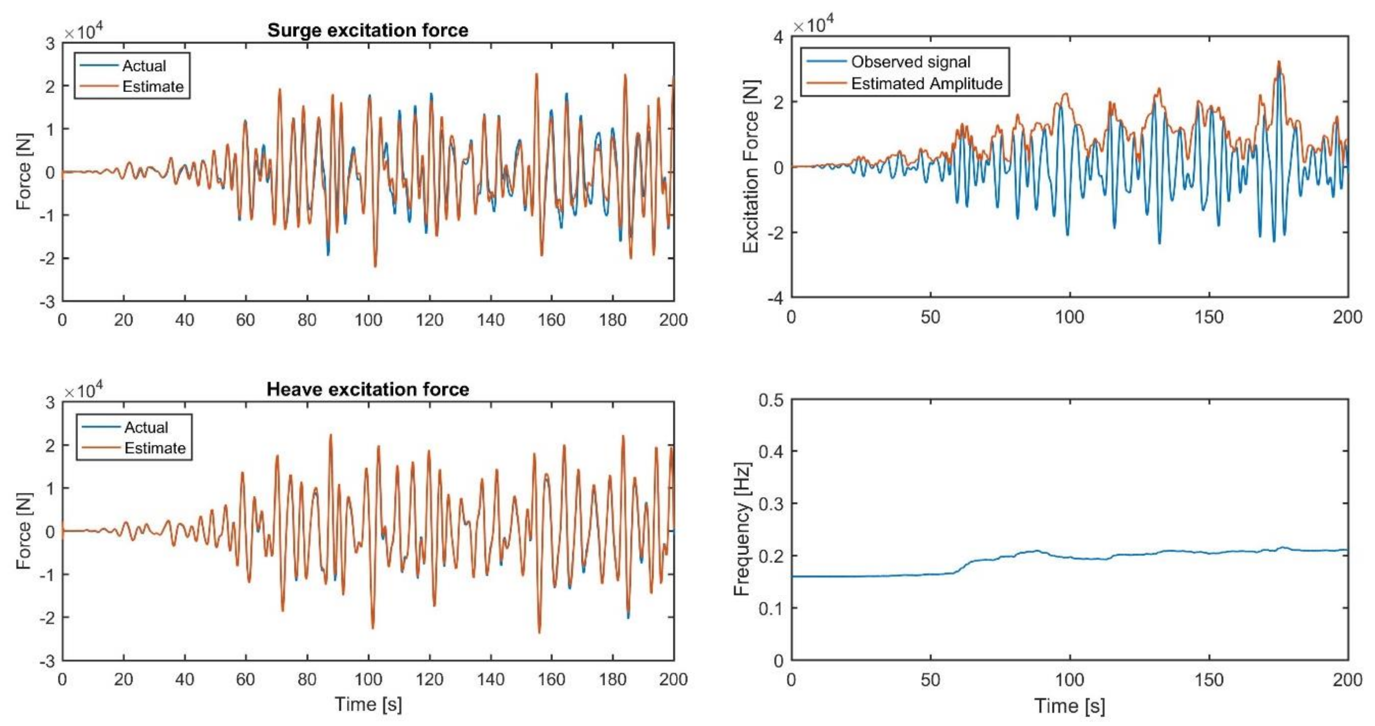
Wave Excitation force estimation

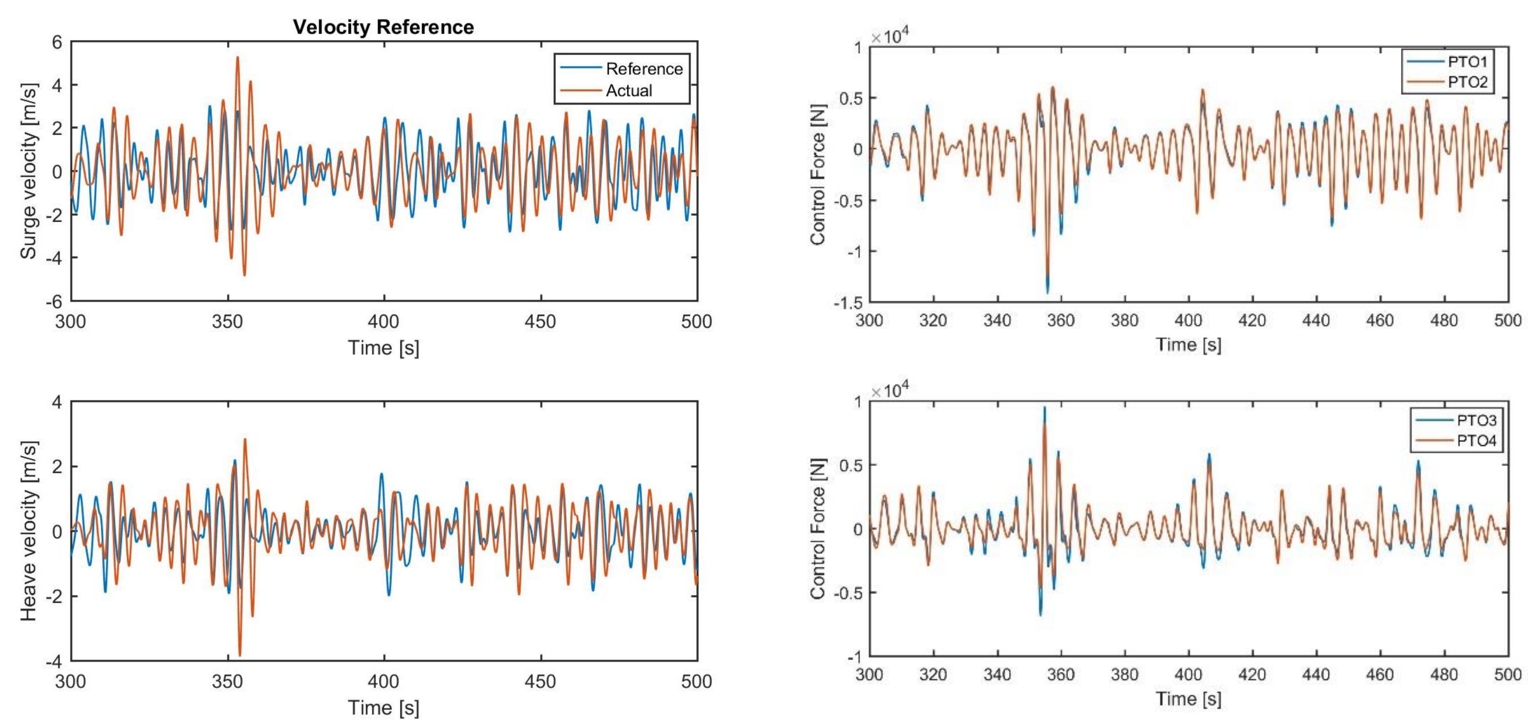
The excitation force is needed to evolve the optimal velocity trajectory for the WEC to follow. The force is not measurable so must be estimated. This is achieved using a classical Observer and Extended Kalman Filtering to estimate the instantaneous amplitude and velocity of the excitation force.

Velocity tracking

A Model Reference Adaptive Controller is used. This can achieve good tracking performance despite modelling uncertainty and nonlinearity. High control accuracy and robustness are simultaneously achieved.



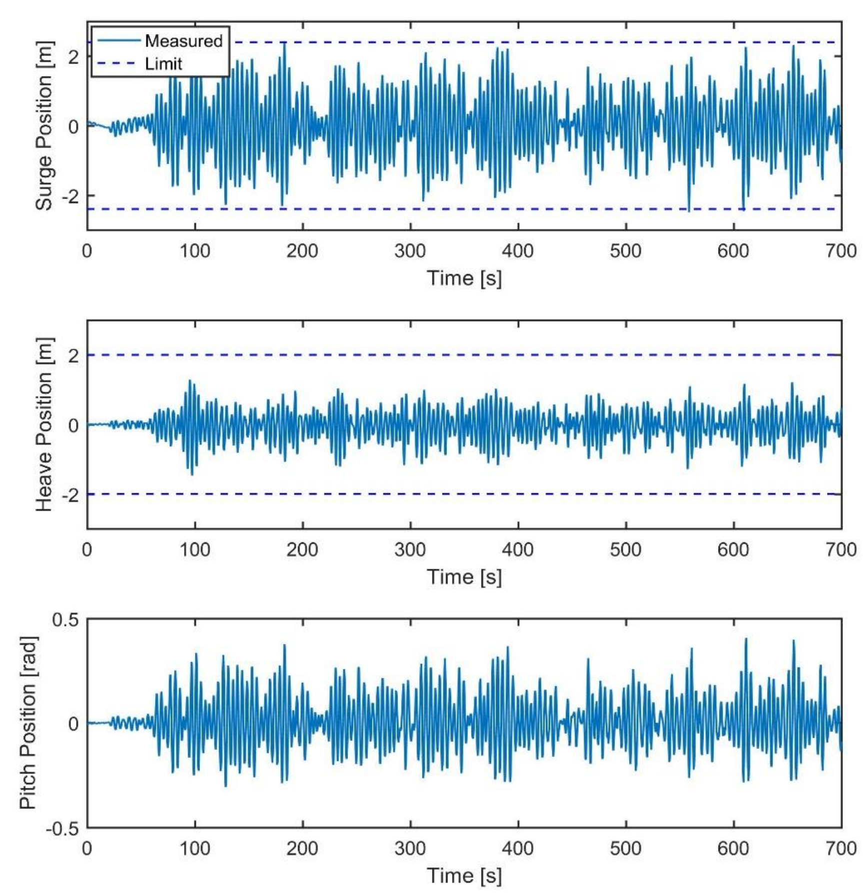


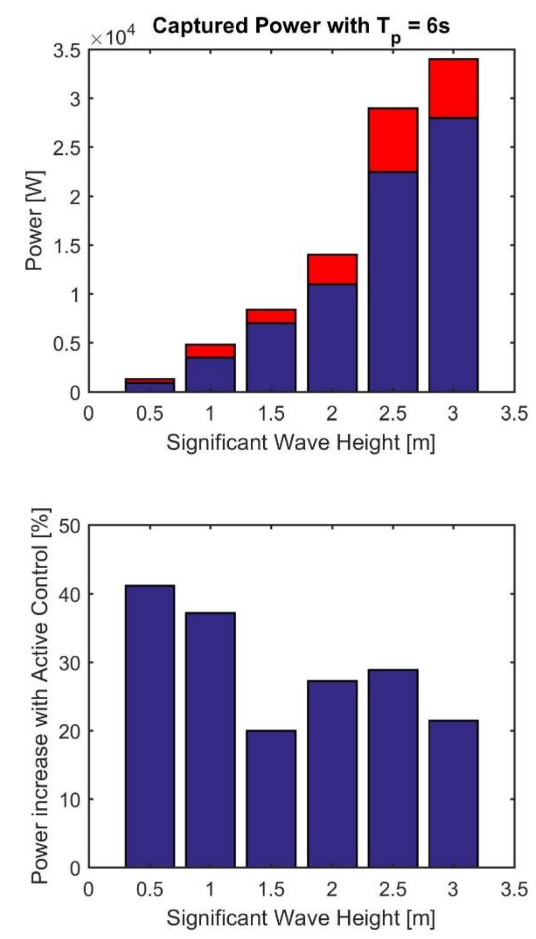


INITIAL ¼ SCALE SIMULATION RESULTS

Initial simulation work has been conducted using a ¼ scale WEC-SIM model of WaveSub. Results indicate that the adaptive strategy can be implemented using no additional sensory information over a passively controlled system. The PTO torque range is comparable to a passively controlled system and the rate of change of torque required is possible with physical architecture. It is readily implemented in either 2-Quadrant or 4-Quadrant form.

Motion outputs show that position constraints are adhered to (the float must not impact on the reactor). Potential pitch motion instability is also alleviated through active control. Mean captured power is increased by up to **40%** compared to the optimal passive fixed damping system in a range of realistic irregular sea states.





FURTHER WORK

Full analysis of performance benefits across a wide range of sea states and model uncertainties with full scale WEC and PTO;
Demonstration of feasibility in terms of: Reliance only upon measurable and available information, real-time implementation and operation within the PTO performance envelope.

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"SURF-MATIC"

Project Overview:

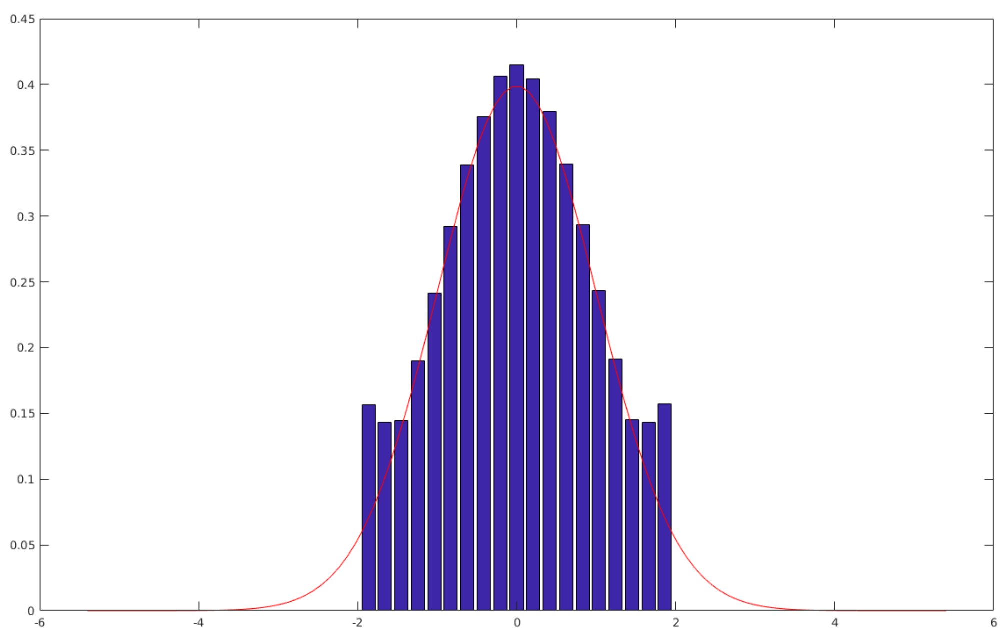
The SURF-MATIC (Survival Focused Automatic Control) project targets development of a control system that is focused on device survival and achieving reduced loading and harshness in Wave Energy Conversion technology.

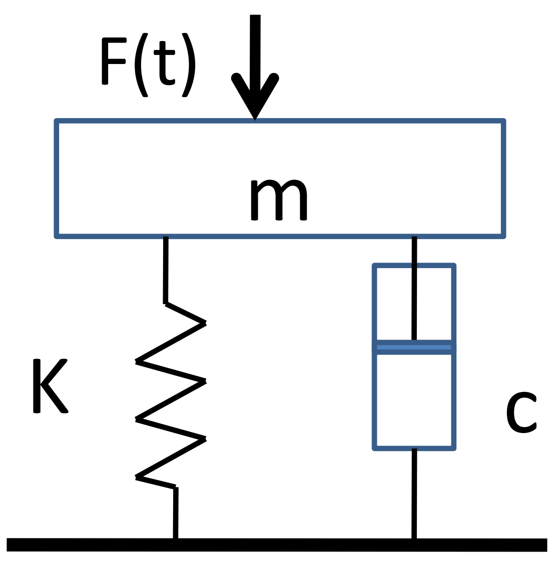
Our Goal:

Investigate ways to achieve ***affordable survivability.***

Survival is one of the strongest cost drivers of the structure in a wave energy converter and the structural cost is a very significant overall proportion of the cost of energy produced. In addition, complications in design due to extreme loadings and harshness also increase the cost and reduce the reliability, availability and performance of subsystems such as power take off and moorings.

Survivability is achievable – however we premise ***"a smarter – more digital – less capital – approach is needed"***





Areas being considered include control systems that:

- Acts to truncate the extreme tails of the structural loading probability distribution by controlling variables that alter the hydrodynamic properties of the device so that it can avoid extreme loads.
- Acts to reduce the occurrence of harshness events such as end stop impacts and tether 'snapping' by controlling variables that both alter the hydrodynamic properties and also alter the dynamic motion response of the device.
- Is generic and can work with a wide range of wave energy converters
- Comes with design tools that can systematically identify (or design in) the configurations for each WEC type that best deliver these benefits.
- Builds on state of the art ultra-high availability control systems (e.g. fly-by-wire) and adapt these to the wave energy application.

The project team:

Wave Venture (Wave Energy Specialists) will gather evidence showing that this approach is valuable and can be achieved for a range of wave energy conversion technologies.

Altran (Control Specialists) will work to show that the proposed system can be delivered in a practical industrial control system that will achieve the ultra-high availability required for safety critical systems at the low cost required in renewable energy.

CorPower Ocean & **Mocean Energy** (WEC developers) will contribute their expert knowledge as technology developers to advise on how best to apply the proposed control technology.