HAPiGYM: Rapid prototyping environments for wave energy control

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Abstract—**Collaborative efforts to promote improved control prototyping could drive the innovation required in the wave energy sector. Previous collaborative efforts have either had a competition or commercial development format. The HAPiWEC project is taking a different approach, named HAPiGYM, whereby participants select from a range of available tools to run experiments on controllers and/or WEC sub-systems. The system was designed following stakeholder engagement, and ongoing response to participant requirements is built into the project. HAPiGYM facilitates a stepped development process, whereby participants progress from testing their systems in a software environment (sandbox), to processor-in-the-loop environments (rig simulator) and finally to tank tests. - The remote access and novel rapid prototyping methods will promote equity of access to the HAPiGYM.**

Index Terms—**automatic code generation, co-design, control, tank testing, wave energy, open hardware, open software, rapid prototyping**

I. Introduction

THE wave energy sector in 2023 has seen significant growth and remains as diverse as ever, with limited signs of convergence, and application areas spanning kilowatt-scale power to large prototypes intended for multi-megawatt arrays for grid-scale electricity or or hydrogen production. Low-power applications include aquaculture, ocean observation, asset monitoring and defence. The cumulative deployment time of prototypes is growing. Examples from across the world include the Yongsoo pilot pilot plant in Korea, the AWS Ocean Energy system in Scotland, C-Power and Oscilla power in US waters, and the King Island UniWave200 project in Australia [1].

Controlling these technologically diverse devices, whether to achieve improved energy yield, overall system cost or reliability, remains an area of academic research [2] and industrial R&D [3]. In academia, recent and notable research projects (building on the early work of [4], [5], and others detailed in [6]) include the Wave Energy Converter Control Competition (WECCCOMP) [7] and FOSTWIN [8].

The early stage development of wave energy converters almost universally involves testing at scale, first in the laboratory (in the form of bench testing and/or hydrodynamic tank testing) and later in the field (for example in a nursery site). Guidance for the early stage development of WECs has been published by the International Electrotechnical Commission: IEC TS 62600-103 [9]. Physical modelling in a wave basin provides a controlled and repeatable environment for benchmarking the performance of WEC technologies, allowing valid and robust comparison of design iterations and operational strategies. IEC TS 62600-103 recognises the importance of control strategies, but there is no formalised benchmarking or comparison process in the guidance. Therefore, there is a need to explore the approaches which most effectively, and efficiently, allow control strategies to be deployed in the very capable wave tank environment.

Wave energy research and development faces the following challenges:

1) Physical testing of devices and their controllers is expensive at sea and at scale in wave tanks.
2) Controllers on control system hardware are often inflexible, necessitating revisited testing.
3) During testing, control engineers must be on the test site which can be inefficient.
4) Due to the large variety of wave energy devices, there is a lack of an open source accessible generic scale model to test new control techniques and compare different approaches.

Consequently, there is insufficient controller testing, the testing benefit (control improvement) is slow, and there are barriers to engagement in wave energy control research. Although testing is generally a mid-TRL activity, (e.g. TRL 6 system model demonstration in a relevant environment), there is a requirement for concept research (e.g. TRL 3) to address the challenges. Against these gaps, and on point 4 particularly, lessons can be learned from other sectors, and the work presented here builds on experiences and outputs across multiple and sustained UK and European research involving the design [10], operation [11], [12] and control [13] of instrumented Horizontal Axis Tidal Turbines (HATTs), where open hardware was designed in academic consortia, and iterated by follow-up work to develop, disseminate and make available test-platforms for a wider range of studies than the

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original scope of work. No such platforms exist for use in the wave sector.

The HAPiWEC project, a 3-year collaboration between Scottish Universities as part of the UK EPSRC Marine Wave Energy call, is a response to these research challenges. On the one hand, the hydrodynamic bodies and PTOs of many WECs are designed and optimised using unrepresentative control policies. The control is either wholly unrepresentative due to over-simplification, or partially unrepresentative, as it addresses only a subset of the control problem. If the WEC is designed using a subset of the operating conditions, then it may not be apparent that only a subset of the control policy is being tested. On the other hand, much cutting edge research on control policies is conducted using models of WECs and PTOs, or operating conditions, that are insufficiently representative. This is a problem because not enough is known about what impact this has on the control problem. There are several good reasons for the use of unrepresentative models, including abstraction, generalisation, standardisation, and simplification as a preliminary modelling iteration. Much of the standards and recommendations for the development of wave energy involves high degrees of abstraction, and there is insufficient evidence to verify that this does not alter the control problem.

The HAPiWEC project set out to address these problems by providing a test rig, initially deployed at the FloWave test tank, that can be accessed remotely, free of charge. Stakeholder consultations to assess the needs of potential participants identified that there was no single type of WEC that would suit a wide range of research needs. For this reason a modular system with a small but growing number of options was chosen, which is named *HAPiGYM*. The name is an analogy to gyms used for physical fitness training, as well as the OpenAI gym [14], which provides software environments for learning AI policies. Ongoing consultations are built into the project plan, to ensure that the HAPiGYM can respond to evolving research needs.

The design drivers are discussed in more detail in Section II. Conflicts between various stakeholder requirements were a major design driver, and the resulting solution is described in the sections that follow: Section III describes the chosen hydrodynamic body; Section IV outlines various aspects of the power take off (PTO), including preload implementation and a real-time PTO simulation; Section V describes the X-in-the-Loop modelling workflow; Section VI describes the control platform; Section VII describes the hydrodynamic model; Section VIII describes how this is incorporated into the rig emulator model; Section IX describes the control hardware and the remote communications; and Section X concludes the paper.

II. Key design drivers

Prior to the design of the apparatus, consultations were held to determine the specifications. The stakeholders consulted fall into three groups: internal, industry, and academia.

The internal group were the HAPiWEC team; the authors of this paper. As a whole, there was a need to deliver the project within the constraints of budget and availability, to leverage existing expertise and resources, to broaden participation, to encourage publication and dissemination, and to create legacy tools that would outlive the HAPiWEC project, providing a flexible platform for future projects and collaborations.

The industry stakeholders included developers of WECs or sub-systems, as well as supporting organisations such as Wave Energy Scotland. We had hoped to attract some participants in the HAPiGYM from this group, however the consultations indicated a mismatch between the needs of this sector and our offer of generic systems in exchange for dissemination of results.

The main way in which HAPiWEC could serve the interests of industry is to ensure that the research outputs were relevant. The solution offered would need to include enough of the real-world challenges such that the controllers developed, or research insights into co-design, were directly applicable to sea-trails of WECs currently under commercial development.

The third stakeholder group are the potential participants in the HAPiGYM: researchers in control policies and co-design, largely based in academia or research institutes such as NREL or Fraunhofer. We aim to broaden participation to include researchers currently excluded to to budget limitations, as well as researchers who don't have access to the full range of specialisms covered in the HAPiWEC project: hydrodynamics, control policies, control hardware, and PTO. To ensure that we are providing a useful tool to researchers, we need to offer flexibility in terms of the system being modelled, and the methods and metrics employed.

The synergies and trade-offs between the needs of these three stakeholder groups gave rise to the HAPiGYM concept, as well as the implementation details described in later sections.

A. Synergies between stakeholder needs

There were several areas in which the interests of all stakeholders were aligned. The need for remote access to a control prototyping tool that included a tank model and control hardware was known at the proposal stage, and formed the basis of the funding application. From the perspective of FloWave, the need for remote access became clear during the COVID-19 pandemic.

There is also wide-spread interest in co-design, both as a research topic and as a necessity in industry to bring down costs. Within the HAPiWEC team there is a research interest in the impact of numerical and experimental methodology on the control problem and conclusions drawn. Any insights would improve guidance on numerical and experimental modelling practices that would benefit future work at FloWave, other research institutions, developers, and funding bodies.

B. Conflict between stakeholder needs

There was a noted mismatch between the needs of device developers and academic researchers of WEC control. Industry needs control prototyping tools that are specific to their WEC, and often to the technical challenges that define the relationship with funders. There is a strong need for confidentiality and protection of intellectual property. Academia needs control prototyping tools that include simple versions for easy entry, which are sufficiently generalised as to be applicable to a range of industrially developed WECs, and sufficiently flexible to adapt to evolving research questions. There is a preference for open-source sharing, dissemination of results, and metrics to allow equitable comparison.

C. Solutions to address synergies and conflicts

Industry and academia have different preferences for the level of modelling abstraction. To address requirements from both groups, the solution was an extendable modular system: a growing collection of GYM machines using common components. The remainder of the paper describes the first two modelling environments. The first GYM machine is a popular research model with one degree of freedom (DoF). The second GYM machine uses the same hydrodynamic absorber in 6 DoF, and is a generalised version of several WECs under commercial development: There will be many common modelling elements in addition to the hydrodynamic shape to limit the effort to move between models.

Extendable 'options' can be added on demand either by HAPiWEC team or in collaboration with participants (open-source curated by HAPiWEC team). A small collection of standardised benchmark cases will allow comparative evaluation and meta-analysis.

III. The Wave Energy Converter

A. WEC family

It was important that this work would be relevant to families of wave energy converters that were currently under commercial development. A review of recipients of industry funding over the previous year [15] showed that the most common WEC families were point absorbers, floating oscillating water columns, and hinged rafts. About two thirds of the devices were self referencing and the remaining third were ground referencing. There were some variations in the number of PTO modes, e.g. some point absorbers applied a control force in one direction only, while others extracted power in three directions.

For our first two GYM machines we chose to offer two variants of the same WEC family: a floating point absorber, reacting against ground via a pretensioned tether. The first variant was restricted to operate in heave only (Figure 1). The second variant was unrestrained and permitted six degrees of freedom (DoF) (Figure 2).

In both cases we chose the simplest method of applying the control force: the PTO acts in a single direction only. In the 1 DoF GYM, the control force will act on the heave DoF. In the 6 DoF freedom GYM, the control force acts in line with the tether, and is a function of the angle at which the tether meets the buoy. This is a compound mode composed of all DoF apart from yaw. If waves are limited to one direction and parametric roll is not excited, the PTO force can be modelled as acting in a single mode composed of heave, surge and yaw components, and can be calculated using trigonometry.

The first variant can be thought of as a warm-up GYM machine. It is intended to ease learning of the HAPiGYM system, and as a non-challenging environment suitable as a first modelling iteration for new research. There is no surge DoF, and so no displacement due to drift. The operating conditions (e.g. waves and preload) made available will include choices to ensure the system is as linear and predictable as possible.

The second variant can be thought of as the workout GYM machine. As there is a DoF in surge, drift will have an impact on the angle at which the tether meets the buoy, and on the mean wetted volume, and hence the hydrodynamic interaction. For ease of transition between GYM machines, the options for operating conditions will include those used in the 1 DoF system. However, there will also be a focus on conditions that provide a more challenging control problem, such as multi-directional waves, and sea states energetic enough to require the imposition of limits on either power capture, velocity, stroke or loads.

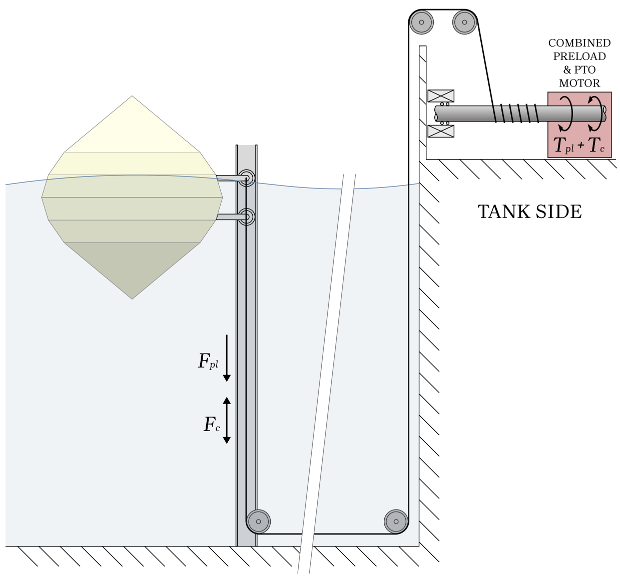

Fig. 1. Simple 1 DoF GYM machine (not to scale).

B. Shape of hydrodynamic body

The float design adopted for HAPiGYM system originates from the 'COERbuoy' WEC concept by Thomas et al. [16]. The preliminary models described here specifically use the COERbuoy float geometry, whilst PTO and mooring arrangements differ to the original system. This device represents a generic non-commercial PA type WEC and was originally designed with consideration of full-scale designs produced by the WEC developer – CorPower Ocean AB [17]. The float is axisymmetric with a profile defined using 7 vertices [18]; the reduced size HAPiWEC variant of COERbuoy is shown in Figure 3.

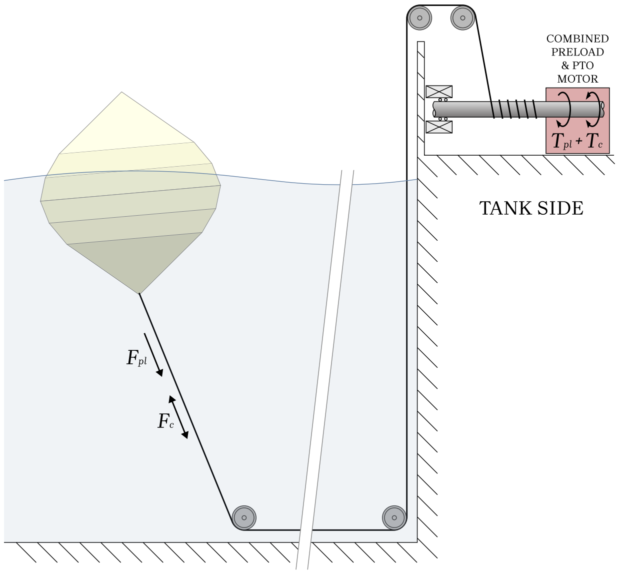

Fig. 2. Simple 6 DoF GYM machine (not to scale).

The COERbuoy is characterised by a range of features which makes this of specific interest for the HAPiGYM system:

- A generalised version of a commercially developed WEC.
- Hydrodynamic coefficients and non-linear FK model have been developed, with publicly available source code and data.
- The device is associated with a control prototyping project with similar aims to HAPiWEC.
- Cross-sectional area varies with draft; this is appropriate for testing nonlinear FK effects on control.
- Geometrically efficient as a wave-maker as it has a higher cross-sectional area near the waterline.
- Its axisymmetry offers greater options for numerical modelling.

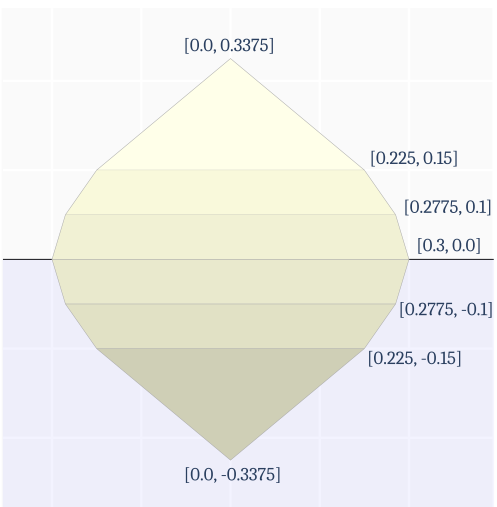

Fig. 3. Side view of complete geometry. The COERbuoy geometry is identical above and below the water plane.

TABLE I
CHOICE OF THREE EQUILIBRIUM WATERLINES WHEN NOT PRE-LOADED FOR A BUOY.

Preload Case	A	B	C
Preload displ. (z_pl)	0.0m	0.075m	0.150m
Unloaded draft (d)	0.337m	0.262m	0.188m
WEC mas	44.5kg	24.9kg	9.9kg
Displaced mass	0.0kg	19.7kg	34.6kg
F_{pl} (constant)	0.0kN	0.19kN	0.34kN
$\|F_{pto}\|$ (cc) $@T = 2s$	9.35kN/m	10.59kN/m	11.53kN/m
$\|F_{pto}\|$ (res) $@T = 2s$	1.09kN/m	1.09kN/m	1.10kN/m

F_{pl} is the pre-load force
F_{pto} (cc) $@T = 2s$ is the PTO force using idealised complex conjugate control at a wave period of 2 seconds
F_{pto} (res) $@T = 2s$ is the PTO force using idealised resistive control at a wave period of 2 seconds

C. Choice of preload and equilibrium waterline

For a point absorber that reacts against the ground using a non-rigid tether, a preload force is required to model bidirectional power capture. Two problems associated with a PTO via a tether are avoidance of forces near the tether's ultimate strength, and avoidance of slack. Slack occurs when the tether tension drops to zero. When the slack line is reloaded it will typically experience a snap load: a high amplitude transient which then sets up a lateral vibration in the tether. Supervisory control can be used to override the demanded control signal. This changes the nature of the control problem: there is an increased challenge to controllers when operating in this regime. In order to offer a GYM machine with a less challenging subset of the control problem, we should offer some nominal conditions where the supervisory controller's slack avoidance does not need to be triggered.

This was one of the considerations when choosing the size of the float. However, there are a few interdependant design parameters. The choice of preload force for a particular size of buoy influences the unloaded equilibrium waterline. Table III-C shows three preload cases A, B and C for the 0.6m diameter buoy.

D. Float size

The float size was derived from a combination of constraints combined with an overall aim of achieving highly energetic conditions for challenging control design. The intent at the outset was to utilise the higher-end of the wave basin's operating envelope. Following preliminary frequency domain calculations of the COERbuoy geometry, a range of float scales were assessed to understand wave condition limits with respect to the passive mitigation of snap loads (contrasting with supervisor control, which provides additional active mitigation). The importance of a large preload force was identified from preliminary PTO forces estimations, indicating the need for a large, low-mass float. Considerations relating to the wave basin (specifically the depth of 2m) and wave conditions led to the selection of a 600mm diameter for the initial implementation of the float. In practical terms, this size allows manufacture on standard milling machines from closed cell foam with a central core to provide a physical attachment for the mooring and also locate onboard instrumentation.

IV. PTO DESIGN

We will be using a motor to actuate the demanded control force. We consider this motor a PTO emulator for several reasons. The first is that it is not a scaled down model of any PTO that would be operating at sea. The real machine would be wound as a generator, rather than a motor, and would be sized with a particular objective in mind, whether that be to optimise LCoE, or reduce risk. The machine in the tank has different objectives: it needs to correctly apply the demanded control force on the hydrodynamic body within representative constraints on power, torque, and speed. The motor rating has not been optimised with respect to the hydrodynamic body. Indeed, there is an opportunity to conduct research into this field by using the motor to model PTOs with ratings lower than the real motor rating. The constraints on power, torque, and speed could then be added as *soft limits*.

A. Preload

As discussed in Section III-C, a preload force is essential for a WEC reacting against ground via a tether, using bidirectional control. There are several implementation options at sea, such as a mechanism referred to as zero-rated or constant force spring, or an air-spring connected to a reservoir. Both of these options offer a large constant force as well as a smaller unavoidable restoring force. The air-spring offers a highly controllable constant force, which is determined by the pressure applied. The restoring force is inversely related to the reservoir volume, so cost considerations guarantee the presence of a restoring force. Air springs also have non-linearities due to temperature variation and changes in operational direction, which can be challenging to model within a controller.

A better solution at this scale is to apply the preload force using a motor. This could either be the same motor applying the PTO force, or a standalone motor. This allows flexibility in application of the preload:

- The preload can easily be set at different levels to model different drafts for the same model, or the same draft when the model's weight has been changed.
- There is an option to simplify the preload to a constant force; this is useful for the simple model for participants to learn on.
- There is an option to model different proportions of constant and restoring force; this might be of interest for designers of preload systems.
- In the future, there is the option to add a simulation of an air-spring; this could challenge control policies to deal with the associated nonlinearities.

For commissioning, the same motor will be used to apply both the preload and the PTO force (far right in Figures 1 & 2). During this process we will learn more about the practical constraints of the system, and that will inform the decision about the operational configuration. At this point, an alternative configuration for the implementation of preload will be considered, as shown in Figure 4.

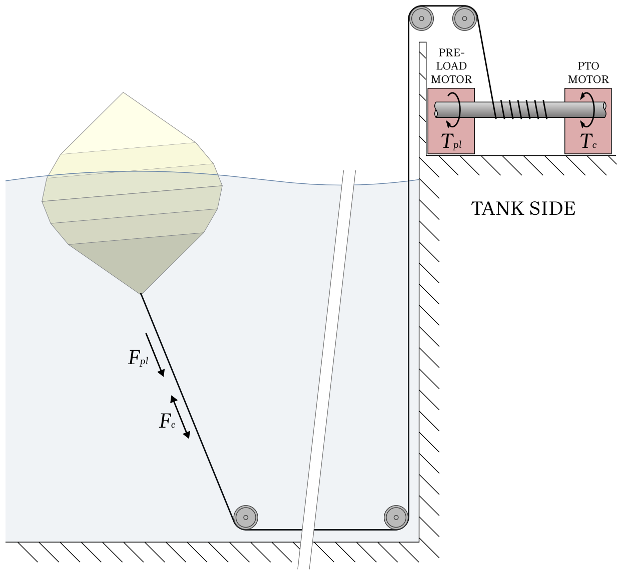

Fig. 4. Alternative for provision of preload - a dedicated motor (not to scale).

B. Choice of motor

The functional requirements for the PTO were modularity and low speed operation. The need for modularity stemmed from the anticipation that the motor would be reused in future gym machines. This would be made possible if there were options to mount the rotor and stator in different configurations. Ideally it should also be light, so that in future work the motor could be placed inside the buoy, or be used with a two-bodied self-referencing device. For this reason we chose a frameless motor and designed the frame ourselves.

A low speed PTO is required to limit the amount of gearing required, which could introduce unrepresentative artefacts such as backlash into the drive train dynamics. The low speed operation has two aspects: low rated speed, and underloaded operation, i.e. below the percentage of rated speed where efficiency drops steeply with decreasing load. There are a couple of reasons why we should expect underloaded operation: one is the reciprocal nature of the WEC's motion; another is a limited degree of intentional PTO oversizing to allow flexibility. For example, we anticipate using the same motor to simulate PTOs of a lower rating than the physical PTO's rating, and in future work the same motor may be used for larger WECs.

For these reasons alone, the PTO will spend most of its time operating at low efficiency. This is of course the main reason why the motor is considered a PTO emulator, rather than a scale model of a PTO. The purpose of the real-time PTO model is to impose more representative PTO efficiencies on to the measured mechanical power. While the motor's efficiency doesn't have an impact on PTO emulation, torque ripples as the speed passes through zero is undesirable for this project. Hence low cogging torque was a key consideration in choice of motor.

Given the inherent underloaded operation, it was important to choose a low rated speed. This requirement needed to be balanced with a sensible voltage range, large enough for high resolution measurements and low noise to signal ratios.

C. Real-time PTO model

As discussed, the motor used in the tank with be a PTO emulator, and the electrical power generated will not be representative of full scale operation. It is only the mechanical power on the shaft which is adequately modelled (using measurements of torque and rotational speed). There is a problem however with using the mechnical power either as a metric or within the objective function within an optimisation: if reactive control (i.e. bi-directional power flow) is allowed, then this would be equivalent to the assumption of a lossless PTO. Optimising for mean mechanical power (even if the reverse power flows are considered) will lead to control policies that unrealistically favour reactive control. It is therefore essential to use the electrical power in metrics and within objective functions.

As the measured electrical power from PTO emulator is not representative, the solution chosen was a real-time PTO simulation. This consists of a PTO efficiency simulation, and a simulation of soft limits. The inputs to the PTO efficiency simulation are the real-time measured mechanical power, torque and rotational velocity, all measured on the motor shaft. The output is the real-time simulated electrical power. This simulation runs both during the Processor-in-the-Loop simulation (Figure 6) and the tank tests (Figure 5). The soft limits of are the operational limits of the simulated PTO: (torque, power, stroke, velocity). None of these may be higher than the hard limits, i.e. the operational limits of the PTO emulator. This gives the option of modelling different PTOs, for example different ratings of the same series of generator.

V. X-in-the-Loop workflow

The workflow will follow a sequence that increases in complexity:

- **Sandbox**: Local simulations on the participant's computer, using the control platform and rig emulator (both can be run in the same simulation)
- **Processor-in-the-Loop**: Remote simulations using control platform and rig emulator.
- **Tank testing:** Remote simulations using control platform and rig in wave tank.

Each step will use different combinations of tools: the control platform (shown in Figure 5 and discussed in Section VI), or the control platform in combination with the rig emulator (as discussed in Section VIII).

The Processor-in-the-Loop and tank testing phases both use remote interfaces to execute the experiment, deploy code, view quasi-real-time simulation results,

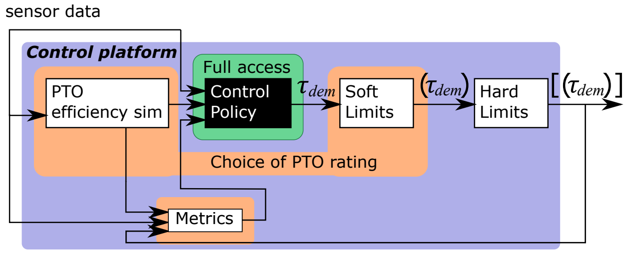

Fig. 5. Control platform for tank tests

and make live changes to set-points during the experiment. These phases will be run in real-time using the HAPiWEC control hardware (see Section IX). During the tank tests the control hardware will be located in the FloWave test tank. During the Processor-in-the-Loop phase the hardware will either be located in one of our laboratories, and accessed remotely, or there will be the option for participants to build their own version of this low cost open-hardware system. The sandbox could be run on the cloud or using local simulations on the participant's own machine. They need not be real time, or interface with any drivers for real time operation on specific hardware components.

Participants need to demonstrate proficiency at each step before being given access to the next level. It is not however a prerequisite that all participants aim for the tank testing phase. HAPiWEC could be used for short student projects as well as PhD level work.

VI. Control platform

The control platform (Figure 5) is used in all the steps of the workflow, from local simulation to tank testing. It will include:

- a model of PTO efficiency
- soft limits
- hard limits
- metrics

A. Hard and soft limits

In line with the overriding ethos of the HAPiGYM approach, the control platform aims to minimise the constraints imposed on the control design process. Rather than a prescriptive approach, participants are allowed as much flexibility as possible. The flexibility is limited purely by either of two factors:

- *Hard* constraints - no access for participants
- *Soft* constraints put in place by the participant

Hard constraints on the control are those that are inherent to the equipment in the tank and the hardware used for the controller. For example, the WEC has a maximum displacement and the PTO is only capable of a given torque, velocity and power. The physical constraints may be accompanied by software constraints for safety purposes (for instance limiting PTO torque demand to 95% of the maximum value).

The *soft* limits are limits imposed by the designer, which inevitably leads to the question 'why limit your design space?'. If HAPiWEC were to have been set up as a competition then the designers would certainly not restrict themselves in this way, however, as HAPiWEC is instead a comparative evaluation, controller designers may wish to investigate and demonstrate their controller's ability to operate with a variety of constraints that may be in place with real devices but that are not a hardware constraint of the rig itself. In this way, participants are able to design their test set up in the manner that best suits them. Soft limits can also be used to model different PTO ratings. This facilitates investigations into the relative sizing of PTOs and hydrodynamic bodies.

For practical purposes the designer is not given full control over the soft-limits, instead, they can choose from a range of pre-designed variants. The available variants are designed with the participants' input, which is an ongoing process. Restricting the variants to a given set prevents unrealistic options from being used, and helps in cross comparison of different control methods when evaluating results. The control policy itself is completely open for the operator to design in whatever way they wish. The only limits are on the available processing power.

B. Variants and options

Figure 5 shows the control platform with boundaries of full access, partial access and no access for participants marked. The orange blocks denote the sub-systems where participants can choose between a limited number of pre-specified variants:

- PTO being modelled: efficiency and rated power
- possibly the fixed preload force
- metrics
- possibly the output of the control policy

The subject of constraints bleeds into the design of metrics, the wave environment, the control inputs used and the design of the PTO. By making the control platform flexible - i.e. minimising hard constraints, and eliminating the competitive aspect of testing, control engineers can look at more interesting cases that drive control technology forward rather than having the design case thrust upon them. As an example, one control engineer may wish to design a controller with minimal sensing inputs for use in more benign conditions, with a novel new PTO that has unusual efficiency characteristics, whilst another may wish to look at using advanced sensing in very energetic seas using off-the-shelf PTO technologies. By keeping the hard limits on the control platform as unconstrained as possible, HAPiWEC aims to facilitate a wide variety of controller designs for a wide variety of control applications.

VII. Hydrodynamic model

The hydrodynamic model will be used in the HAPiGYM Sandbox and Processor in the Loop (PiL) environments within the HAPiWEC project. It should be capable of delivering rapid and accurate estimations of the device response to wave excitation. Two alternative open-source models have been chosen for this task: (1) the well-known WEC-Sim software [19]

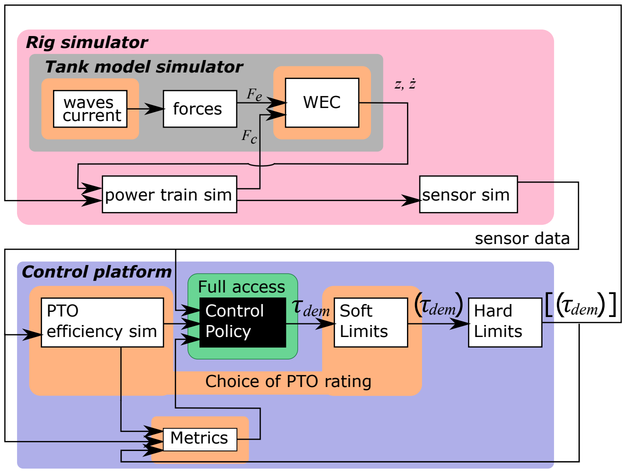

Fig. 6. Control platform and rig simulator

and (2) OceanEd, a software package developed in the University of Edinburgh [20], [21]. HAPiWEC users can then select which of the two packages they would prefer to use. Both software packages are time-domain models based on the standard linear Cummins' equation approach. OceanEd was originally developed for interacting WEC arrays and it uses a single state-space system to approximate all the radiation interactions between all the degrees of freedom.

In order to make these above codes sufficiently accurate, it is necessary to include additional nonlinear fluid forces into the equations of motion. These forces could include nonlinear Froude-Krylov (FK), nonlinear scattering (note, the Froude-Krylov plus the scattering force equals the diffraction force), nonlinear radiation, nonlinear hydrostatic (note, some researchers refer to this as the static part of the FK force) and nonlinear viscous forces.

Of the above forces, work by Giorgi and Ringwood [22]–[24] and others point to wider evidence that highlights the relative importance of the nonlinear FK and hydrostatic forces in the wave energy problem, particularly for devices that are small relative to the incoming waves. As a result, much of the emphasis within the HAPiWEC numerical hydrodynamic modelling will be on the accurate representation of these two nonlinear forces.

A number of existing open source models are currently available which treat nonlinear FK loads. Three such models have been identified as potential implementation options to support the hydrodynamic modelling requirements: WEC-Sim [19], COERbuoy Platform [25], and NLFK4ALL [26]. The standard WEC-Sim distribution incorporates an optional nonlinear FK model component, in which nonlinear pressure formulations are evaluated on a panel-by-panel basis. Simon et al. [25] consider nonlinear FK, radiation and diffraction; this involves ensembles of re-orientated linear solutions compiled as look-up-tables from which interpolations are carried out during the time domain simulation. The approach taken by Giorgi et al. [27] (NLFK4ALL) offers a set of efficient numerical solutions to an algebraic method, which is specifically suited to axisymmetric devices (as is relevant to HAPi-

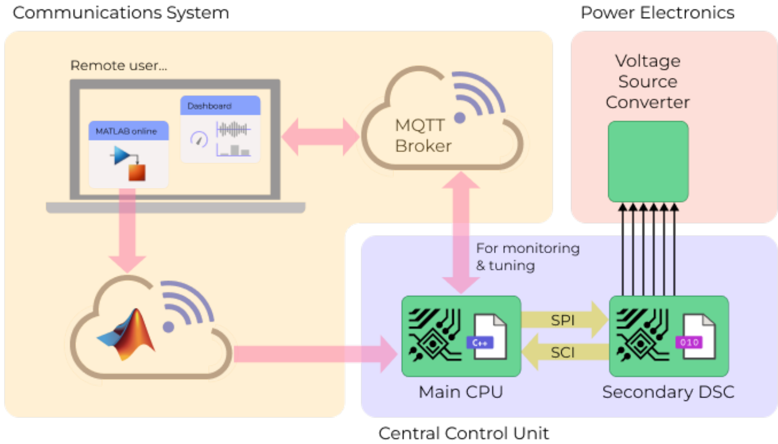

Fig. 7. Layout: Processor-in-the-Loop.

WEC). Of these nonlinear FK models, WEC-Sim and NLFK4ALL are implemented in MATLAB/Simulink; the COERbuoy Platform is written in Python.

VIII. Rig emulator model

The hydrodynamic model is labelled the *Tank model simulator*, and is shown in the grey box in Figure 6. The input (F_c, the reaction force due to the action of the PTO) and outputs ($z, \dot{z}$ position and velocity) pertain to the hydrodynamic body. The rig simulator (pink box in in Figure 6) contains the tank model simulator augmented with additional transformations:

- Encoder and sensors: representative noise added to measured values, quantised and delayed (sensor sim)
- Transformation of forces and translations at the buoy to torque and rotations at the spindle (power train sim).
- Actuator: representative noise added to measured values, quantised and delayed (power train sim).

The orange blocks denote the sub-systems where participants can choose between a limited number of pre-specified variants:

- GYM machine: e.g. 1 DoF or 6 DoF buoy.
- Hydrodynamic modelling method.
- Resource: waves, possibly current.
- Possibly the level of preload.

IX. Control hardware and User interface

A. Control hardware requirements

In the HAPiWEC project, users are naturally led to solve closer-to-real-world problems by developing their controller in line with the requirements of industrial systems: discretisation of control structures at the appropriate sampling time, processing constraints of embedded digital systems and signal processing. Still, the HAPiWEC project provides enough flexibility and computational capacity to alleviate real-world problems for the users. This includes remote accessibility, rapid software prototyping using visual languages and modular software/hardware. All these capacities are provided by HAPiWEC using a selection of low-cost solutions that can be reproduced by research teams elsewhere.

B. Chosen control hardware

The capacities of the HAPiWEC project are enabled by four main subsystems with the corresponding functionality:

1) Main CPU
   - Real-time running of WEC control platform.
   - Remote communication with the user.
   - Data logging.
2) Secondary Digital Signal Controller
   - Rig simulator for processor-in-the-loop and Sandbox.
   - Low-level control: Power electronic control, state machines, high-frequency sampling, PWM, filtering.
   - Real-time scheduling and timing pulse generation.
3) Power Electronic System
   - IGBT switches.
   - Gate Drives.
   - temperature and current sensing.
4) Communication systems
   - Remote experiment monitoring and control.
   - Remote deployment of executable code to the Main CPU.
   - Logged data download.

A full schematic diagram of these subsystems is presented in Figs. 7 and 8.

Together the main CPU and secondary digital signal controller (DSC) make up the central control unit. For the HAPiWEC project, a 1.5 GHz 64-bit quad core ARM Cortex-A72 processor single-Board Computer (SBC) has been selected to run the real-time processes of the policy controller at a sampling rate of around 100ms. This SBC includes 8 GB of onboard RAM, and up to 2TB of flash memory (SD card), as well as a variety of peripherals, including an IEEE 802.11ac wireless module which is ideal for data logging and wireless communication with the remote user. This device has a raw processing power of 3,190 floating-point MOPS, which is close to a base-level commercial real-time target computer, and provides the user the capability to deploy four simultaneous processes (one

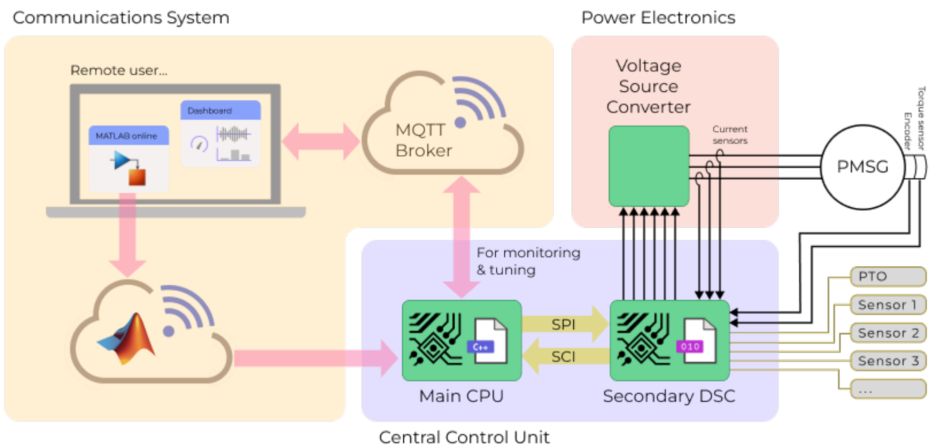

Fig. 8. Layout: tank tests

per processor) in their control structure. Furthermore, by using task-scheduling, each processor can run separated tasks at different sampling rates.

The High-frequency sampling and conversion of sensor signals, as well as the closed-loop control of generator dynamics and the generation of deterministic pulse-width modulation (PWM) signals for the power electronic converters, is handled by the secondary digital signal controller. Additionally, the DSC uses its fast execution process to enforce the hard constraints of the control platform. By using a high-speed Serial Peripheral Interface (SPI) communication channel, the main CPU synchronises with the DSC and sends set-points and control commands (such as torque or speed references) to the power electronic converter of the generator. In turn, the DSC provides real-time sensor data to the main CPU for high level control and data logging purposes. The secondary digital signal controller selected for this project is the Texas Instruments TMS320F2838D which is a 200MHz, 32-bit, 2-core, 2-co-processor controller. Its peripherals include analog to digital converters, SPI ports, and PWM modules. The parallel processing power of the 2 cores and 2 co-processors or the DSC is used to deploy the low-level control of the power electronics, the rig emulation and the state machines that enforce hard limits and monitor the safety and operation of the experiment.

The experiment requires power electronics for the purposes of controlling the WEC's electrical generator, becoming itself the actuator in the control system structure. To avoid using expensive machine drives and maximize flexibility, this project relies on the STEVAL IPM30B evaluation kit for industrial power modules. This evaluation kit is a highly configurable 3KW 3-Phase Voltage Source Converter capable of driving up to 400V DC signals at a peak current of 35A [28]. The cost of the kit is below 100 dollars and provides PWM inputs, short-circuit rugged IGBTs, gate drives, as well as over-current protection and features such as under-voltage lockout, smart shutdown, temperature sensing, and NTC thermistors. The system achieves accurate and fast conditioning of current feedback to satisfy typical requirements for field-oriented control of electric machines.

C. Remote signal communications

With regards to the external communication from/to the system to/from the user, a lightweight over-the-internet communication protocol which requires low computational resources and is cheap to use has been selected for this project. This protocol is called MQTT and will be implemented in the master CPU controller to provide users with up to 8 data snapshots updated every second. Each snapshot could consist of a single data (1 point per second) or 30 continuous data sampled at a desired sampling rate to visualize dynamics events. The users will have full freedom to select which signals to monitor within their control process. Parallel to this, a PC-based graphical user interface (GUI) will be designed to retrieve from the internet and plot the experiment data using several 2D axes. The GUI will also make use of the MQTT protocol to send data from the user to the main CPU to define control set points and reference values at a 1 second sampling rate. Figure 9 shows the design of the GUI for remote user monitoring and control.

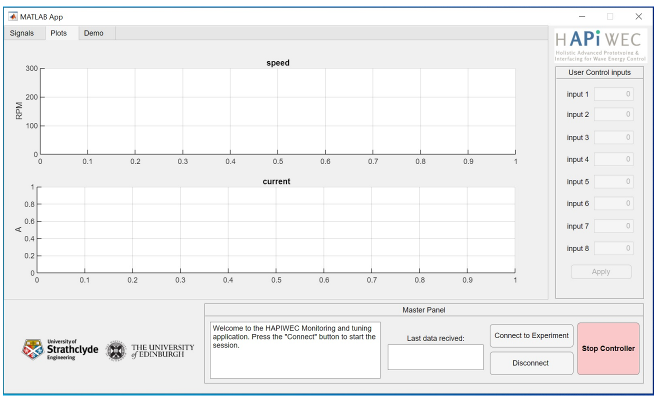

Fig. 9. The MATLAB GUI environment.

D. Remote deployment

Finally, to give the users the capability to deploy their own control policies into the remote experiment, the HAPiWEC project provides access to a special MATLAB-Simulink online environment where users can develop, simulate, compile and deploy a real-time control program into the master CPU at the experiment location with the push of a button. This feature not only allows users to program the experiment control policy but also enables the fast prototyping of control systems, since users can use visual language (Simulink) to create control structures and rely on the automatic code generation tools of matlab to deploy embedded code compatible with the master CPU.

X. Conclusion

The HAPiGYM is a solution to the conflicting requirements of researchers into WEC control, who need an easy entry point to a control prototyping tool, and the wider WEC community, who need research into WEC control to be relevant and directly applicable to the challenge of commercialising wave energy conversion. It is a growing collection of open-source rapid prototyping environments for WEC control policies. Each GYM machine will have both experimental and simulated versions. We will offer a finite number of configuration options. This is a trade off between flexibility and standardisation.

Through presenting the current iteration of the HAPiGYM in this paper, it is hoped that further discussion and academic debate can be stimulated. It is important to note that the design process will continue throughout and, hopefully, beyond the HAPiWEC project, evolving continually as informed by new scientific developments.

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