Moment-based nonlinear energy-maximising optimal control of wave energy systems to secure a renewable future

Work Package WP1

Extension class of nonlinearities

Deliverable D1.2

Report on WP1

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Executive Summary

This documents constitutes Deliverable 2.1 of the H2020-MSCA-IF-2020 **Destiny**'s project (Grant Agreement No 101024372). *Destiny is a project dedicated to advance the state-of-the-art of WEC control technology by providing a novel and reliable nonlinear optimal control framework, maximising energy absorption for a wide range of ocean conditions for single and multiple devices, exhibiting real-time capabilities and globally optimal performance. The final aim is to provide all stakeholders in the wave energy field with a fundamental tool to facilitate reaching economic viability of wave energy technology.*

In particular, this document constitutes a report of the work done throughout work package 1 (WP1), on the **extension of the class of nonlinearities** within moment-based optimal control for wave energy systems, and its corresponding synergy with the remainder of the project. Two fundamental steps have been taken to achieve such an objective, including: 1) incorporation of input-dependent nonlinear effects (both hydrodynamic- and control-related), and 2) derivation of global optimality conditions for the extended nonlinear control framework, including the development of support tools to guarantee and assess such conditions in practical applications.

As such, the *main* contributions of this WP can be summarised as follows:

1. Development of a data-based framework for control-oriented modelling of nonlinear input-dependent hydrodynamic and actuator effects.
2. Extension of moment-based optimal control theory to fully incorporate 1).
3. Derivation of the set of globally optimal conditions for 2).
4. Development of a set of tools to support 2), and guarantee and assess 3) in practical applications.

The tools developed throughout WP1 have a direct impact on the subsequent package WP2, which aims at the experimental validation of moment-based optimal control for wave energy systems.

1 Project overview

Ocean waves have an enormous potential, capable of fulfilling 20% of the global energy demand, making a decisive contribution towards a low-carbon energy society, addressing number 7 (affordable and clean energy), 11 (sustainable cities and communities), and 13 (climate action) of the United Nation Development Goals. As a matter of fact, to achieve the 2030 Climate & Energy Framework and the Roadmap 2050 targets, the European Union (EU) highly encourages development of the ocean renewable energy field, which can potentially mitigate EU dependence on fossil fuels, directly contributing to Europe's decarbonisation goals by 2030 and 2050. Despite being a vast resource, wave energy converters (WECs) have not yet been successfully commercialised. The lack of proliferation of wave energy can be attributed to its current levelised cost of energy (LCoE), which is substantially higher than other renewable energy sources (see *e.g.* (Ringwood, Bacelli, & Fusco, 2014)).

Control system technology can impact WEC design and operation, by maximising energy extraction from waves, and optimising energy conversion in the power take-off (PTO) actuator system. In particular, the central problem in WEC control is to find a technically feasible way to 'act' on the device (via the PTO) so that energy absorption from waves is maximised while minimising the risk of component damage (Faedo, 2020; Faedo, Olaya, & Ringwood, 2017). Such a control process can be written in terms of an *optimal control problem*, where the objective is to design a suitable control algorithm capable of enhancing the performance of WECs, as schematically illustrated in Figure 1. It is already clear that control technology can enhance WECs performance in a wide range of ocean conditions, substantially reducing the LCoE. In other words, the design of appropriate control technology, together with an economy of scale facilitated through array configurations, constitute key stepping-stones towards successful commercialisation of WEC technology.

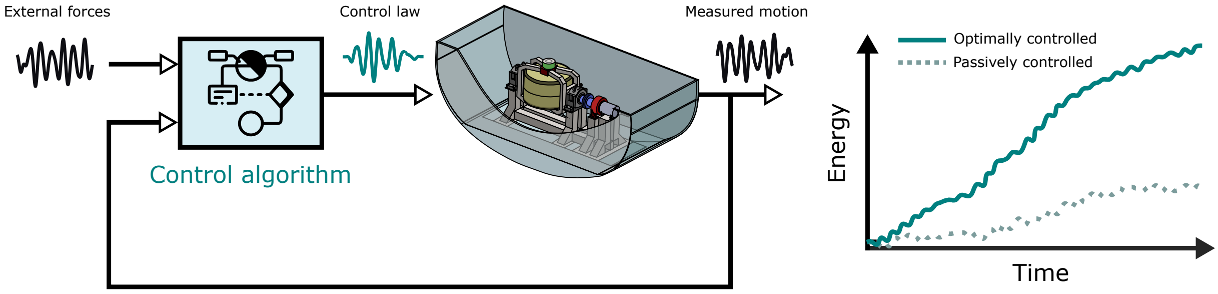

Figure 1: Schematic diagram of optimal WEC control.

Using knowledge from both the external forces (such as the force exerted by waves), the measured motion of the device, and a suitable control-oriented dynamical model, an optimally designed control algorithm can substantially increase the energy absorbed from the wave resource. A particularly efficient control framework for wave energy systems is based upon the notion of moments (Faedo, Scarciotti, Astolfi, & Ringwood, 2021a, 2021b; Faedo, 2020). *Moments* are mathematical objects which relate to the steady-state response of the WEC device, being able to transcribe the energy-maximising infinite-dimensional optimal control problem for wave energy extraction systems, to a computationally tractable optimisation program. To achieve this, moment-based theory combines a number of fundamental concepts arising in system dynamics and control, including centre manifold theory, approximation theory, and the concept of invariance (see *e.g.* (Isidori, 2013)), as schematically detailed in Figure 2.

Though already efficient and highly competitive, moment-based control for WECs still requires of development to thrive in real-world scenarios. **Destiny** will greatly advance the state-of-the-

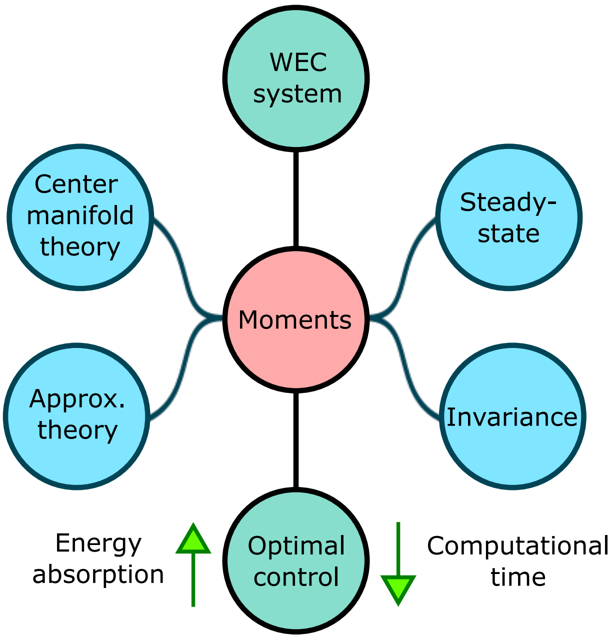

Figure 2: Schematic diagram of moment-based theory and WEC control.

art of this family of controllers, by means of four (4) main research objectives (ROs), each of these associated with a specific work package (WP), as follows (see also Figure 3):

- **RO1–WP1 (Extension class of nonlinearities)**: The first core research objective of Destiny is to extend the nonlinear moment-based WEC control framework by including relevant IDNs in the corresponding energy-maximising OCP. This will systematically guarantee optimal performance for a large class of devices, featuring an accurate nonlinear description of the WEC dynamics, directly advancing the state-of-the-art of WEC control.
- **RO2–WP2 (Controller validation)**: The second core objective of Destiny is to perform a full experimental validation of the extended moment-based nonlinear control framework, allowing its reliable utilisation in real-world scenarios.
- **RO3–WP3 (Extension to WEC arrays)**: The third core research objective of Destiny is to incorporate multiple devices to the newly extended (via WP1) and fully validated (via WP2) nonlinear moment-based framework, hence being able to include arrays in the energy-maximising control design procedure, advancing the state-of-the-art of WEC control, following and supporting the pathway towards effective commercialisation of WEC technology.
- **RO4–WP4 (Software release)**: The final core research objective of Destiny is to release an open-source software, ‘Control for all’ (CONTRALL), to design and test the novel moment-based controller for a given (user-selected) device. CONTRALL will be readily available, coded in a user-friendly environment, directly benefiting WEC developers and stakeholders in the process of design and commercialisation of both existing, and novel devices.

As such, the control framework resulting of **Destiny** will feature an accurate description of the physics associated with the wave energy extraction process, optimally maximising energy absorption for single devices and array configurations, and exhibiting real-time capabilities. This will provide all stakeholders in the ocean engineering and wave energy fields with a fundamental and easily accessible tool to facilitate reaching economic viability of WEC technology.

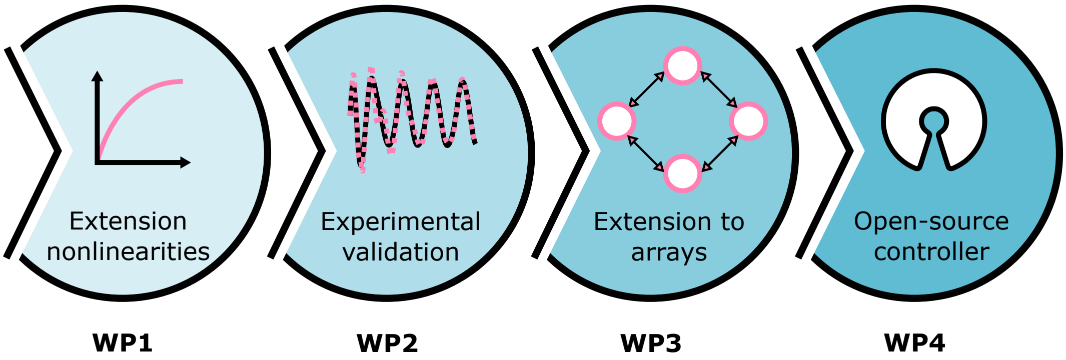

Figure 3: Destiny WPs and their synergy and interconnection.

2 Objectives and main contributions of WP1

2.1 Specific objectives

The objectives of this specific work package comprise two main items:

1. Extension of moment-based optimal control for wave energy systems to include input-dependent nonlinear effects (*i.e.* wave- and actuator-dependent nonlinearities).
2. Guarantee well-posedness of the control solution.

Given the ultimate objective of **Destiny**, *i.e.* delivering a general framework for optimal control of wave energy systems, Item 1) above is required to greatly extend the class of WEC systems that can be incorporated to the proposed nonlinear moment-based approach, while Item 2) guarantees that the resulting control problem is both effectively optimal, and consistently solvable.

A number of contributions have been originated while achieving 1) and 2), including a set of complementary tools to further facilitate practical implementation of the proposed moment-based control solution in realistic experimental environments, *i.e.* to support the pathway from WP1 to WP2. A full list of the research publications associated with the contributions of WP1 can be found here in Section 3. Note that final author versions for every published publication can be openly downloaded from the POLITO IRIS repository.

2.2 Roadmap WP1

Figure 4 illustrates the main technical components of WP1, along with the corresponding list of associated contributions in form of peer-reviewed research publications (see Section 3). Such interacting and fundamental parts of WP1 are listed in the following:

- *Unknown-input estimation* - Publication (1).
- *Incorporation of nonlinear input-dependent effects via moment-based theory, model reduction, and system identification* - Publications (5), (7) and (9).
- *Optimality ensurance* - Publication (2).
- *Optimality assessment* - Publications (3) and (8).

Each of these fundamental components, and their associated contributions, are described in detail within Section 4, along related tutorial/application cases (Publications (4) and (6)).

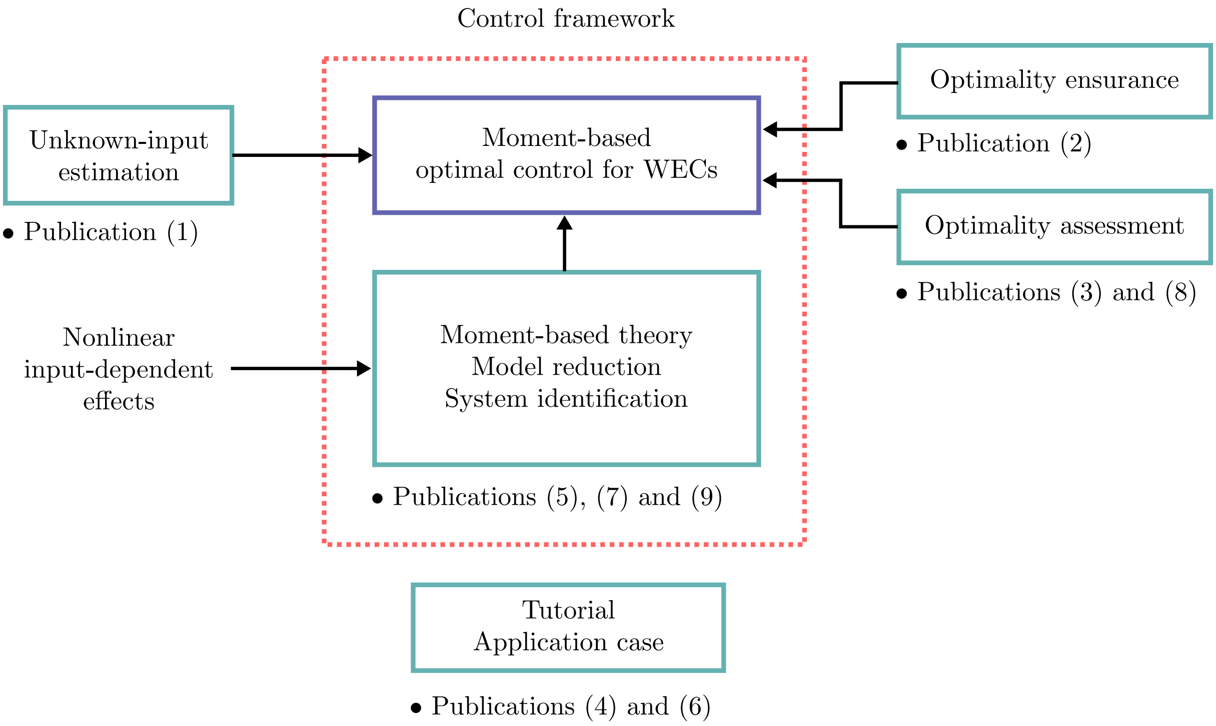

Figure 4: Schematic illustration of WP1 main contributions.

2.3 Contributions

Unknown-input estimation

As schematically depiced in Figure 1, the computation of the WEC optimal control law depends upon knowledge of the external inputs acting on the WEC system (either the so-called free-surface elevation, or the associated wave excitation force, see *e.g.* (Peña-Sanchez, Windt, Davidson, & Ringwood, 2019)). These are often unmeasurable (*i.e.* uncontrollable), so that a suitable *unknown-input estimator* is required to effectively compute such signals.

To date, observers for WECs are often based upon 'complex' techniques, which are counter-intuitive in their design, additionally requiring an explicit model to describe the external inputs as part of an (augmented) system. The latter imposes strong assumptions on the design of each estimator, while also implying an additional computational burden associated with the necessity of augmenting the WEC model to include the dynamics of the input.

In the light of this, a *simple* and *effective* unknown-input estimator is proposed within WP1, which does not require an explicit model of the input. In particular, the unknown-input estimation problem for WEC systems is re-formulated as a tracking control-loop, so that a wide-variety of design techniques (arising from either classical or modern control theory) can be used to compute an estimate of the unknown input.

The theoretical and practical aspects of the proposed technique are discussed in detail within Publication (1), including a high-fidelity case study based upon computational fluid dynamics (CFD) environments.

Input-dependent nonlinearities via moment-based theory, model reduction & system identification

Two general classes of input-dependent effects are vastly present within accurate dynamical modelling of wave energy systems: Wave- and actuator-depentent effects. We describe these, and the fundamental contributions of WP1 towards effective incorporation of such effects within optimal moment-based WEC control, in the following paragraphs.

As the fundamental purpose of a WEC is to effectively maximise energy absorption, which readily translates into an increase in operational range of motion (see *e.g.* (Davidson, Giorgi, & Ringwood, 2015)), nonlinear dynamical effects acquire relevance, and non-representative linear models may become inaccurate. For a large variety of devices currently in development, such as heaving point absorber WEC systems, a significant nonlinear contribution of the hydrodynamic force is the so-called **wave-dependent** *Froude-Krylov* (FK) effect (or force), which directly arises as the integration of the incident pressure field over the wetted surface of the device (Giorgi & Ringwood, 2017). Though a significant effort has been put in accurate numerical modelling of FK forces within the WEC literature (for both static and dynamic cases), optimal control design and synthesis, capable of effectively taking into account such nonlinear FK effects, is rather scarce. Furthermore, **actuator-dependent**, *i.e.* power take-off (PTO), nonlinear effects are also inherent to WEC systems (Bacelli, Genest, & Ringwood, 2015), given the level of sophistication often required to effectively transform the energy from ocean waves into electricity. As such, complex PTO systems are now dominant, and hence their accurate modelling within control procedures becomes fundamental to achieve maximum energy extraction.

Motivated by the lack of both suitable control-oriented modelling techniques for input-dependent effects, and optimal control algorithms capable of effectively incorporating such nonlinear behaviour into the computation of a corresponding energy-maximising control law, this WP1 approaches two main objectives for this class of nonlinear effects. Firstly, a fully data-based framework for the approximation of nonlinear input-dependent effects in terms of mathematical structures compatible with state-of-the-art control procedures is proposed. Secondly, a full extension of optimal moment-based WEC control methodology to the case of WEC systems subject to input-dependent nonlinearities is proposed, being able to preserve the attractive properties characterising the moment-based direct transcription. It is further demonstrated that the proposed data-based procedure effectively fits with the control design requirements, *i.e.* there is a well-defined synergy between modelling and optimal moment-based control, rendering an overall control procedure capable of achieving maximum energy extraction, with real-time capabilities.

Further detail on the contributions, and associated technical details, reported in this section, can be directly found in Publications (5), (7) and (9).

Optimality ensurance

As reported in Publications (7) and (9), existence of globally optimal solutions for the extended moment-based nonlinear controller heavily depends upon a property termed *passivity* (Faedo et al., 2021a). Passivity, with an additional set of technical assumptions, refers to the capability of the WEC system to dissipate internal energy.

While standard WEC modelling procedures *should* deliver passive models, dynamical structures adjusted via experimental testing, *i.e.* real data, might not necessarily automatically fulfill this fundamental property. Motivated by this, an optimisation-based approach to passivation of

WEC systems is proposed in this WP1, aiming at guaranteeing existence of globally optimal solutions for the extended nonlinear moment-based controller. In particular, a suitably designed system perturbation is introduced to the underlying control-oriented WEC model, computed via minimisation of a linear objective, subject to a specific set of linear matrix inequalities (LMIs), which can be solved efficiently using state-of-the-art and readily available LMI solvers. Unlike the (very few) available methods available in the WEC literature, the proposed passivation strategy does not require the a-priori localised detection and quantification of passivity violations, hence being both straightforward to apply, and efficient to solve, given the linear nature of the optimisation objective.

The technical details and theoretical results related to this strategy have been reported in Publication (2).

Optimality assessment

Most wave energy systems present relevant dynamics in more than a single degree-of-freedom (DoF). Furthermore, not only WECs are inherently multi-DoF, but naturally *underactuated*: Energy is often extracted from a single DoF, while the device effectively moves in multiple modes of motion. This complicates the derivation of an explicit set of optimality conditions under idealised conditions, *i.e.* a benchmark optimality case for effective controller assessment, which is currently widely used in the single DoF case (see *e.g.* (García-Violini, Faedo, Jaramillo-Lopez, & Ringwood, 2020)).

To the best of our knowledge, neither a formal discussion, nor a full derivation of the optimal energy-maximising conditions for underactuated wave energy harvesters allowed to move in several modes of motions, *i.e.* underactuated multi-DoF WEC devices, has been presented in the literature of WEC control to date, hence precluding the natural extension of the optimality assessment criterion to realistic and potentially complex WEC systems.

In the light of this, a comprehensive derivation and discussion on the idealised optimal control conditions for maximum energy absorption in underactuated multi-DoF WEC systems is derived as part of WP1. In particular, the optimality principle for single-DoF devices is extended to underactuated multi-DoF systems, and a set of optimality conditions is explicitly derived. In addition, the impact and use of this set of optimal conditions for control design and synthesis is explicitly discussed. Among such design and synthesis conclusions, it is shown that the core design of optimal energy-maximising controllers for underactuated multi-DoF systems *only depends upon the dynamics of the controlled DoFs*, and that any uncontrolled modes of motion can be ‘left out’ from the energy-maximising design, substantially simplifying the controller synthesis procedure. This, naturally, provides a powerful theoretical framework to support the activities of WP2 (experimental validation) and WP3 (extension of moment-based control to WEC arrays).

Technical details behind the proposed set of optimality conditions for controller assessment, can be found in Publication (3).

Tutorial & application cases

Deep understanding of moment-based control, and moment-based theory in general, typically requires a background in applied mathematics, system dynamics, and/or control theory. Aiming to facilitate a smooth application of the proposed control techniques for non-specialised control academics and/or industrial engineers, Publications (4) and (6) present application cases of moment-based control for different WEC systems.

In particular, Publication (4) presents an overview of moment-based theory for wave energy systems, including a detailed description of each design and synthesis step characterising the proposed WEC optimal control procedure.

Publication (5) presents a detailed application of moment-based control for a particular wave energy system, providing also a thorough comparison with state-of-the-art control techniques, showing a consistently improved performance.

3 List of publications associated to WP1

This section contains a list of peer-reviewed publications (in chronological order), which constitute outcomes/results associated with WP1. The following shorthand notation is used to denote the status of the publication: (P) published, (UR) under review.

Final author versions for every published (P) publication can be openly downloaded from the POLITO IRIS repository.

Nº	**Status**	**Publication**
(1)	(P)	N. Faedo, U. Bussi, Y. Peña-Sanchez, C. Windt and J. V. Ringwood, “A simple and effective excitation force estimator for wave energy systems”, *IEEE Transactions on Sustainable Energy*, 2021.
(2)	(P)	N. Faedo, Y. Pena-Sanchez, F. Carapellese, G. Mattiazzo and J. V. Ringwood, “LMI-based passivation of LTI systems with application to marine structures”, IET Renewable Power Generation, 2021.
(3)	(P)	N. Faedo, F. Carapellese, E. Pasta and G. Mattiazzo, “On the principle of impedance-matching for underactuated wave energy harvesting systems”, *Applied Ocean Research*, 2021.
(4)	(P)	N. Faedo and J. V. Ringwood, “A control design framework for wave energy devices”, 14th European Wave and Tidal Energy Conference (EWTEC), Plymouth, 2021.
(5)	(P)	N. Faedo, F. J. Dores Piuma, G. Giorgi, G. Bracco, J. V. Ringwood and G. Mattiazzo, “Data-driven nonlinear model reduction by moment-matching for the ISWEC system”, IEEE ICECCME, Mauritius, 2021.
(6)	(P)	N. Faedo, D. Garcia-Violini, Y. Pena-Sanchez, J. V. Ringwood, “On the feasibility of energy-maximising controllers for an Argentinian wave energy systems”, XIX Workshop on Information Processing and Control (RPIC 2021), San Juan, 2021.
(7)	(UR)	N. Faedo, G. Giorgi, J. V. Ringwood, G. Mattiazzo, “Optimal control of wave energy systems considering nonlinear Froude-Krylov effects: Control-oriented modelling and moment-based control”, *Nonlinear Dynamics*, 2021.
(8)	(UR)	F. Carapellese, E. Pasta, B. Paduano, N. Faedo and G. Mattiazzo, “Intuitive LTI energy-maximising control for multi-degree of freedom wave energy converters: the PeWEC case”, *Ocean Engineering*, 2021.
(9)	(UR)	N. Faedo, G. Mattiazzo, J. V. Ringwood, “Robust energy-maximising control of wave energy systems under input uncertainty”, 2022 European Control Conference, London, 2022

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Faedo, N. (2020). *Optimal control and model reduction for wave energy systems: A moment-based approach* (Unpublished doctoral dissertation). Department of Electronic Engineering, Maynooth University.

Faedo, N., Olaya, S., & Ringwood, J. V. (2017). Optimal control, mpc and mpc-like algorithms for wave energy systems: An overview. *IFAC Journal of Systems and Control*, *1*, 37–56.

Faedo, N., Scarciotti, G., Astolfi, A., & Ringwood, J. V. (2021a). Nonlinear energy-maximizing optimal control of wave energy systems: A moment-based approach. *IEEE Transactions on Control Systems Technology*, *29(6)*, 2533–2547.

Faedo, N., Scarciotti, G., Astolfi, A., & Ringwood, J. V. (2021b). On the approximation of moments for nonlinear systems. *IEEE Transactions on Automatic Control*, *66(11)*, 5538–5545.

García-Violini, D., Faedo, N., Jaramillo-Lopez, F., & Ringwood, J. V. (2020). Simple controllers for wave energy devices compared. *Journal of Marine Science and Engineering*, *8*(10), 793.

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Disclaimer

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