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Extending the Operational Availability of Wave Energy Systems

Maynooth Wave Energy Workshop 2026

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2. Health-Aware Control (HAC)
3. Fault-Tolerant Control (FTC)
4. Conclusions

Introduction

1. The wave energy industry is still in its infancy in terms of its **technology readiness level (TRL)**¹.
2. The continued development of WEC control strategies is essential for improving the techno-economic feasibility of wave energy through **levelised cost of energy (LCoE)** reduction.
3. **Using LCoE as a control objective is challenging because LCoE is not available in real-time, and its calculation is complex and uncertainty-dominated.**

¹Bingyong Guo and John V Ringwood. "Geometric optimisation of wave energy conversion devices: A survey". In: *Applied Energy* 297 (2021), p. 117100.

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$$\text{LCoE} = \frac{\text{CapEx} + \text{OpEx}}{E},$$

where

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- However, EMC tends to cause exaggerated device motion, accelerating lifetime degradation and reduction of reliability.

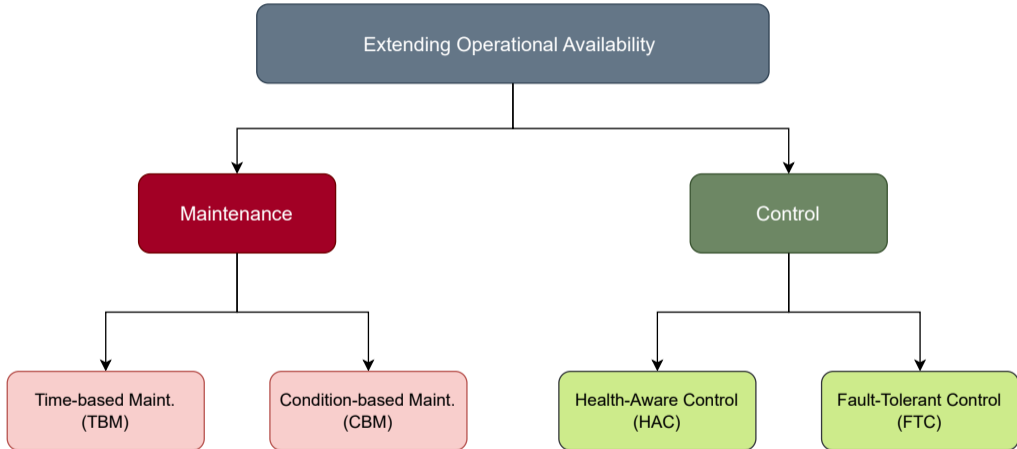
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- However, EMC tends to cause exaggerated device motion, accelerating lifetime degradation and reduction of reliability.
- Increased maintenance frequency and repair induce an increase of OpEx.
- **Loss of operational availability due to failures also induce an increase of LCoE.**



Health-Aware Control (HAC)

Energy-maximising control ¹

Simple frequency-domain controllers:

- Typically based on the **impedance-matching** principle (e.g., LiTe-Con).
- While conceptually simple, constraint handling is challenging

Constrained optimal controllers:

- Typically formulated as an **optimisation** problem (e.g., EMPC).
- Although more complex, constraint handling can be guaranteed.

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Health-aware control ²

Incorporating the WEC health status, χ , into the control objective yields *health-aware control*, enabling **a deliberate trade-off** between energy capture and WEC lifetime.

Remark:

In the energy-maximising EMPC, the extra terms are included to preserve convexity—they are **not** health-aware terms.

¹John V Ringwood, Siyuan Zhan, and Nicolás Faedo. “Empowering wave energy with control technology: Possibilities and pitfalls”. In: *Annual Reviews in Control* 55 (2023), pp. 18–44

²Amin Ziaei, Hafiz Ahsan Said, and John V Ringwood. “Health-sensitive control of wave energy converters: A primer”. In: *Ocean Engineering* 311 (2024), p. 118893

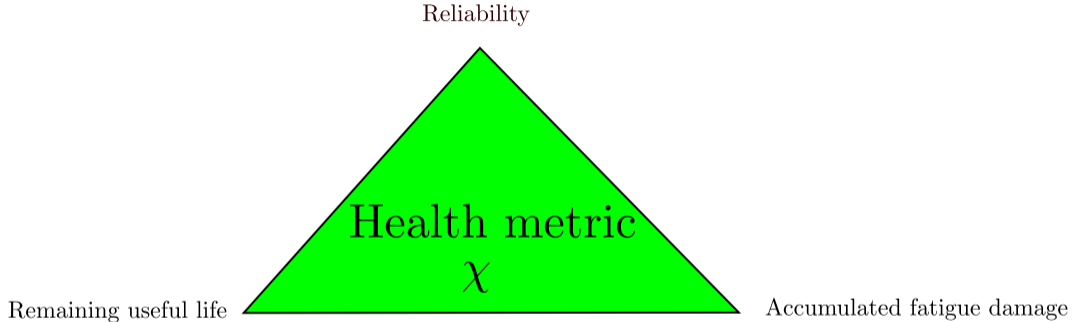


Figure 1: Health metrics³.

³A Ziaei, HA Said, and JV Ringwood. "Health aware control of wave energy converters: Possibilities and challenges". In: *Innovations in Renewable Energies Offshore (2025)*, pp. 559–567.

Health-aware WEC control approaches⁴

Direct approach:

$$\max_{f_{PTO}^{ref}(t)} J = E(f_{PTO}^{ref}(t)) + q\chi(f_{PTO}^{ref}(t)), \quad \text{Subject to: } \begin{cases} \text{WEC model,} \\ \text{Physical constraints,} \end{cases}$$

where $f_{PTO}^{ref}(t)$ is the control signal, and q is a trade-off parameter.

Indirect approach:

$$f_{PTO}^{ref}(t) = f_{PTO}^{nom}(t) + qf_{PTO}^{ref}(t - \tau)$$

where $f_{PTO}^{nom}(t)$ is the control input provided by an energy-maximising controller, and $\tau \rightarrow \chi(f_{PTO}^{ref}(t)) > \chi(f_{PTO}^{nom}(t))$.

⁴Amin Ziaei, Hafiz Ahsan Said, and John V Ringwood. "Reliability-driven health-aware control augmentation strategies for wave energy converters". In: *Energy Conversion and Management: X* (2025), p. 101501.

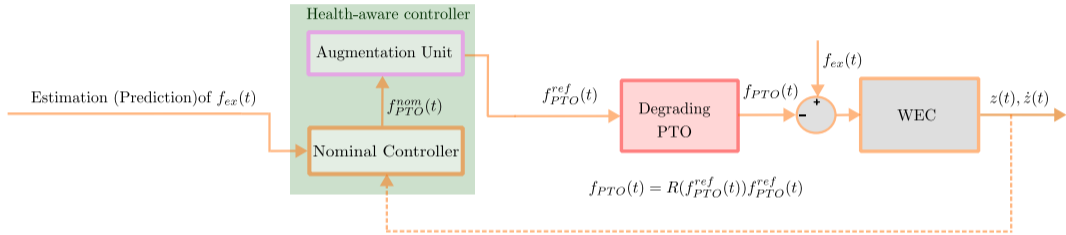


Figure 2: Block diagram of the proposed health-aware control augmentation⁵.

⁵Amin Ziaei, Hafiz Ahsan Said, and John V Ringwood. "Reliability-driven health-aware control augmentation strategies for wave energy converters". In: *Energy Conversion and Management: X* (2025), p. 101501.

Trade-off between energy and device Lifetime

Each point in Figure 3 represents (E, χ) , equivalently $(E, OpEx)$, with the main selection criterion given by LCoE, though factors such as electricity price may also apply.

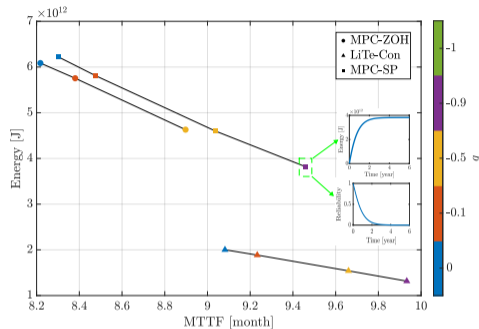
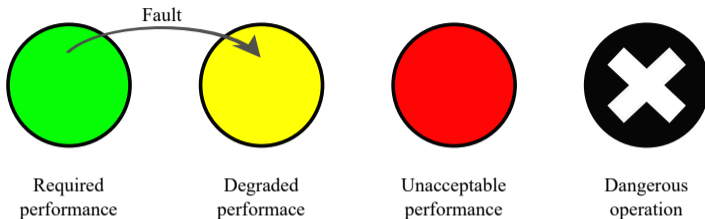


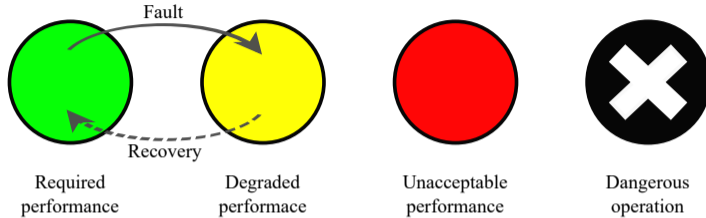
Figure 3: The trade-off between energy and device Lifetime (MTTF) using the indirect approach^a.

^aAmin Ziaei, Hafiz Ahsan Said, and John V Ringwood. "Reliability-driven health-aware control augmentation strategies for wave energy converters". In: *Energy Conversion and Management: X* (2025), p. 101501.

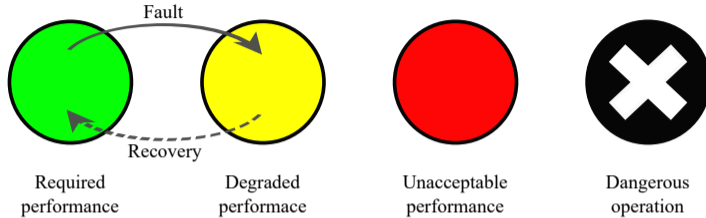
Fault-Tolerant Control (FTC)



- A **fault** is a deviation of the system structure or parameters from their supposed nominal (normal) condition.
- A **failure** refers to the inability of the system or component to accomplish its function.



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- If a diagnosed fault is **recoverable**, FTC aims to achieve the **required** performance.
- For **non-recoverable** faults, FTC aims to preserve an **acceptable** performance.



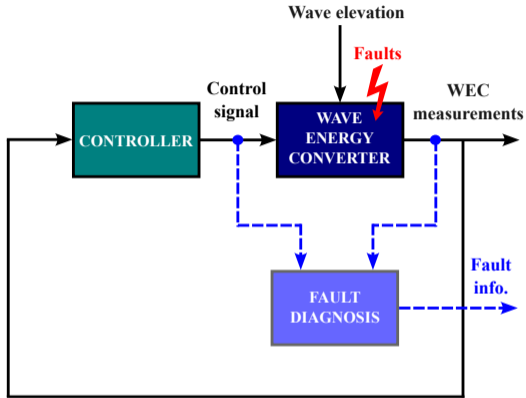
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- Regarding **wave energy conversion**, FTC can provide a **cost-saving solution** during the time between the occurrence of faults and the weather window for maintenance.

Some studied faults in WECs⁶

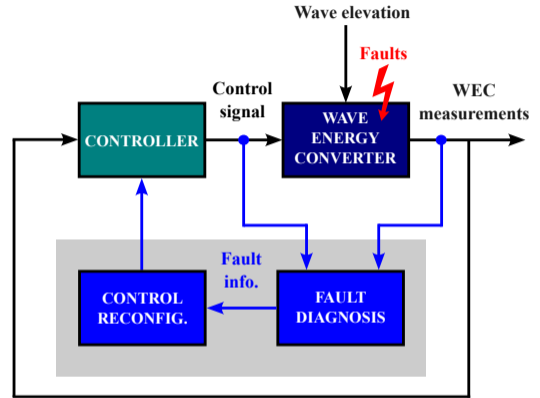
- Wave absorber
 - Biofouling
 - Tank perforation
 - Damper damage
 - Position and velocity sensor faults
- Power take-off
 - Runaway speed of turbines
 - Corrosion on the turbine shaft
 - Ball-screw pitting and wear⁷
- Generator + Electric power converter
 - Generator overspeed
 - Power switch faults

⁶Hafiz Ahsan Said, Augusto C. Sardá, and John V. Ringwood. *“Fault management in wave energy systems: Diagnosis, prognosis, and fault-tolerant control”*. In: *Ocean Engineering* 316 (2025), p. 119794. ISSN: 0029-8018.

⁷Alejandro Gonzalez-Esculpi et al. *“Fault diagnosis of a wave energy converter based on ball screw mechanism”*. In: *Proceedings of the European Wave and Tidal Energy Conference*. Vol. 16. 2025



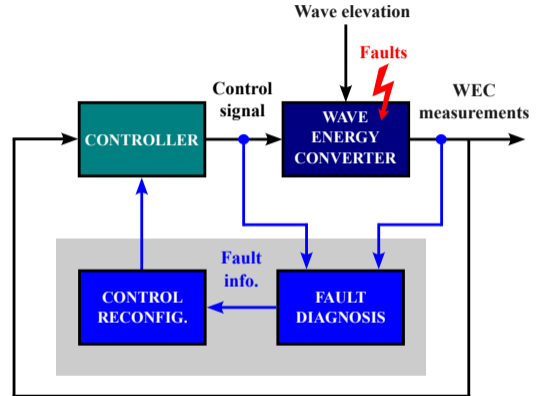
Passive FTC



Active FTC

Main challenges for **fault diagnosis** (FD) and **fault-tolerant control** (FTC) in WECs

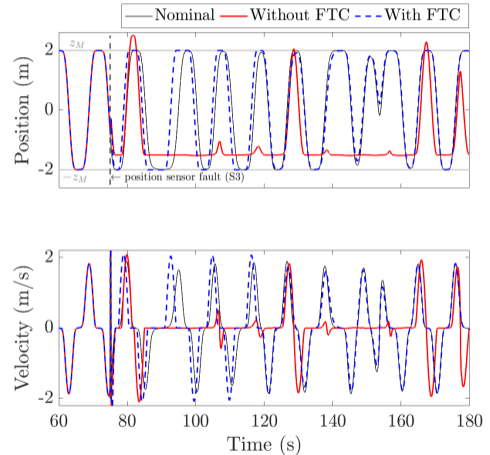
- Inaccuracy of linear model in the presence of exaggerated motion
- Uncertainty in the excitation force estimate.
- Hydrodynamic phenomena such as drag force and nonlinear hydrodynamic stiffness.
- Scarce information about the long-term operation of WECs.



Example

Position sensor fault in a point absorber WEC

- Energy-maximising controller with motion constraints.
- The fault in the position measurement is compensated.
- FTC is able to recover the nominal performance.



Conclusions

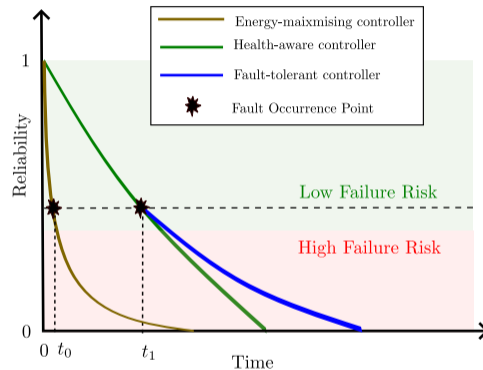
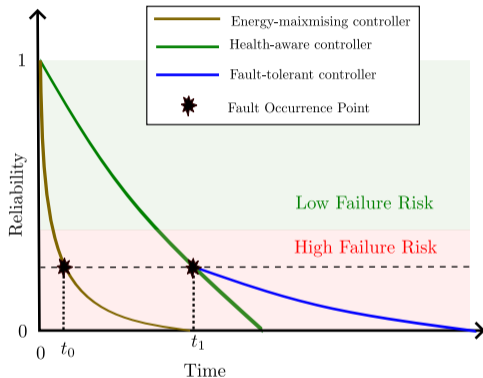


Figure 4: Illustration of degradation path model based on reliability and possible faults

Health-Aware Control (HAC)

- Prevents failure by focusing on accumulated fatigue damage, reliability and remaining useful life.

Fault-Tolerant Control (FTC)

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Although assessing the economic impact of both HAC and FTC in WECs remains a difficult task, their features contribute to extending the operational availability and, as a consequence, reducing the LCoE.

Thank you!



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