NORTH WIND

SINTEF

NTNU

15 January 2025

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NorthWind – Diagnostic Digital Twin for Anomaly Detection in Floating Offshore Wind Energy

FME NorthWind

NORTH WIND

WP1: Structures and Integrity

WP2: Marine Operations and Logistics

WP2: Electrical Infrastructure & System integration

WP4: Digital Twin & Asset Management

WP5: Sustainable Wind Development

Project stats:

- 2021-2029 duration
- 350+ MNOK budget
- 50 Industry partners
- 21 PhD Candidates
- 30+ Innovations in development

Research

SINTEF, NTNU, NGI, UiO (University of Oslo), NINA (Norwegian Institute for Nature Research)

Associates

DTU, EUI (Florence School of Regulation), Fraunhofer, ForWind (Zentrum für Windenergieforschung), RISE, University of Strathclyde Glasgow, NREL (National Renewable Energy Laboratory), TNO

Industry

ABB, Aker Offshore Wind, ANEO, aibel, Renewables Norway, DNV, DOF, equinor, Finnmark Kraft, FORCE Technology, Fred. Olsen Seawind, Hafslund, Hydro, Kongsberg, NOV, Nexans, NKT, Norconsult, Oceaneering, Statkraft, eviny, Store Norske, TotalEnergies, VARD, Amon Wind, Baker Hughes, EDP Renováveis, ESVAGT, Olav Olsen, GFMS, Huisman, NorSea, Odfjell Oceanwind, WorldWideWind, Renergy, Sustainable Energy, Norwegian Energy Partners, Norwegian Offshore Wind

A Digital Twin is …

- … virtual representation of a physical asset enabled through data and simulators in real-time for various purposes.
- … defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making (Rasheed, San, Kvamsdal, 2020).
- … a virtual representation synchronized with physical things, people, or processes (NVIDIA, 2021).
- .. a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making (IMB 2020).
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- … a digital representation of a real-world entity or system. The implementation of a DT is an encapsulated software object or model that mirrors a unique physical object, process, organization, person, or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city, and their related processes (Gartner).
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Digital Twin Capability Levels

Standalone | Descriptive | Diagnostic | Predictive | Prescriptive | Autonomous

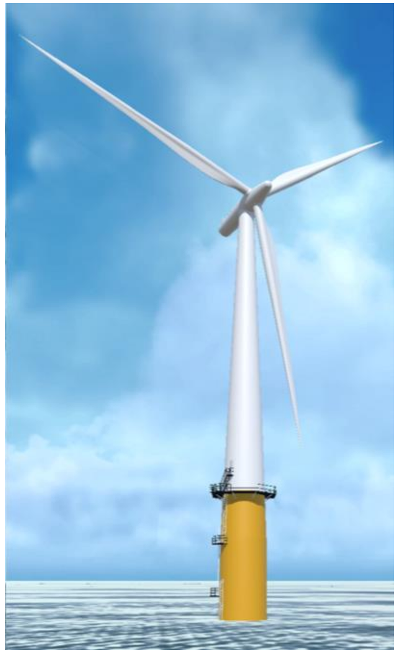
Physical turbine

Manual data transfer

Human User

Design, planning

Virtual representation



Digital Twin Capability Levels

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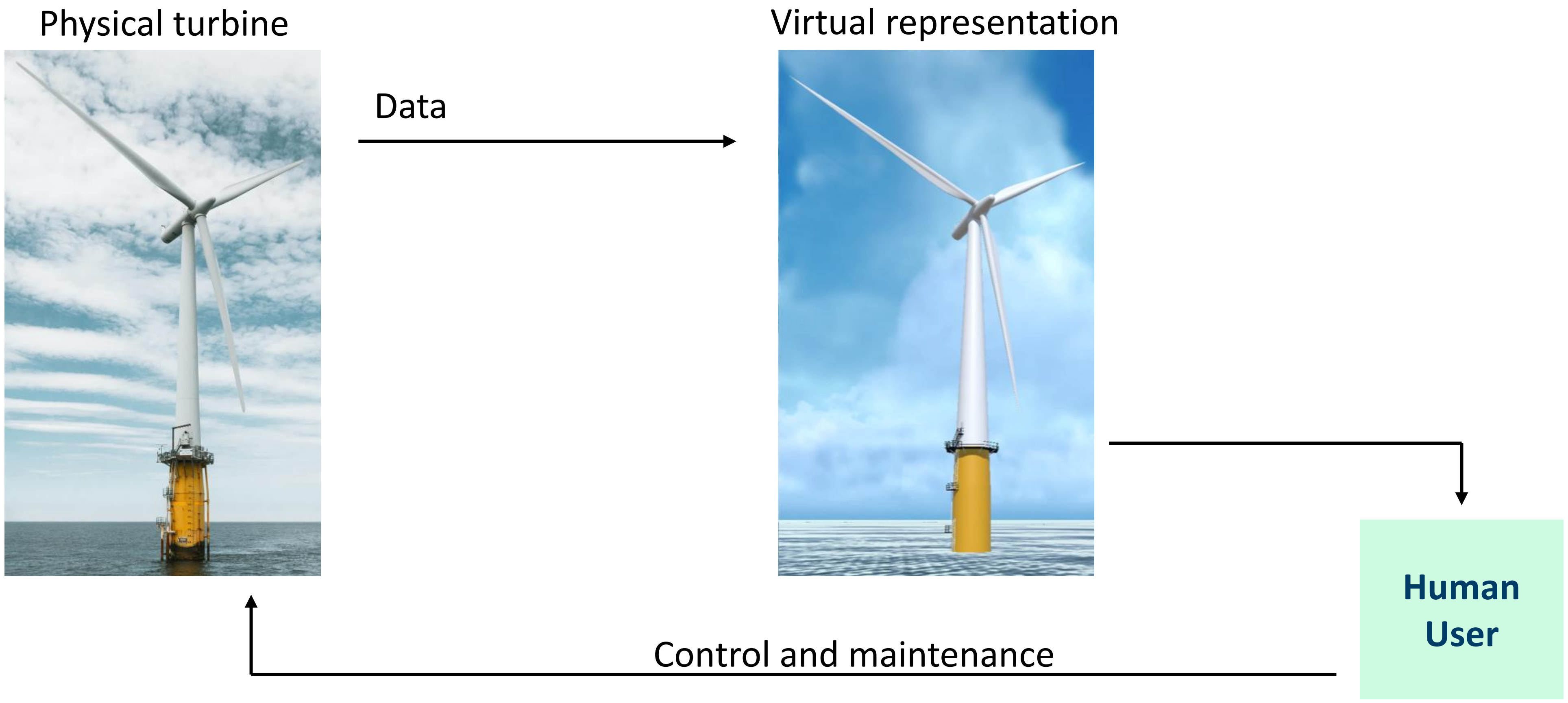

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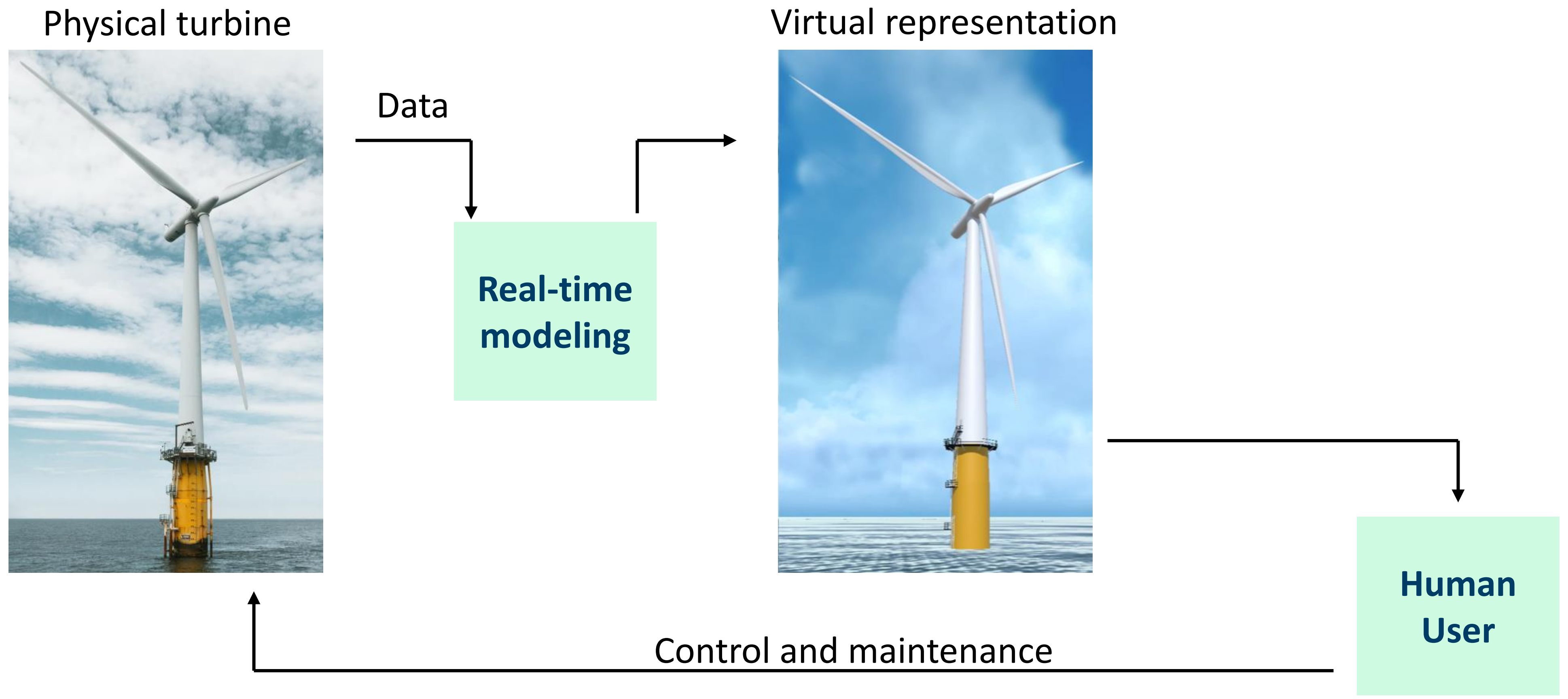

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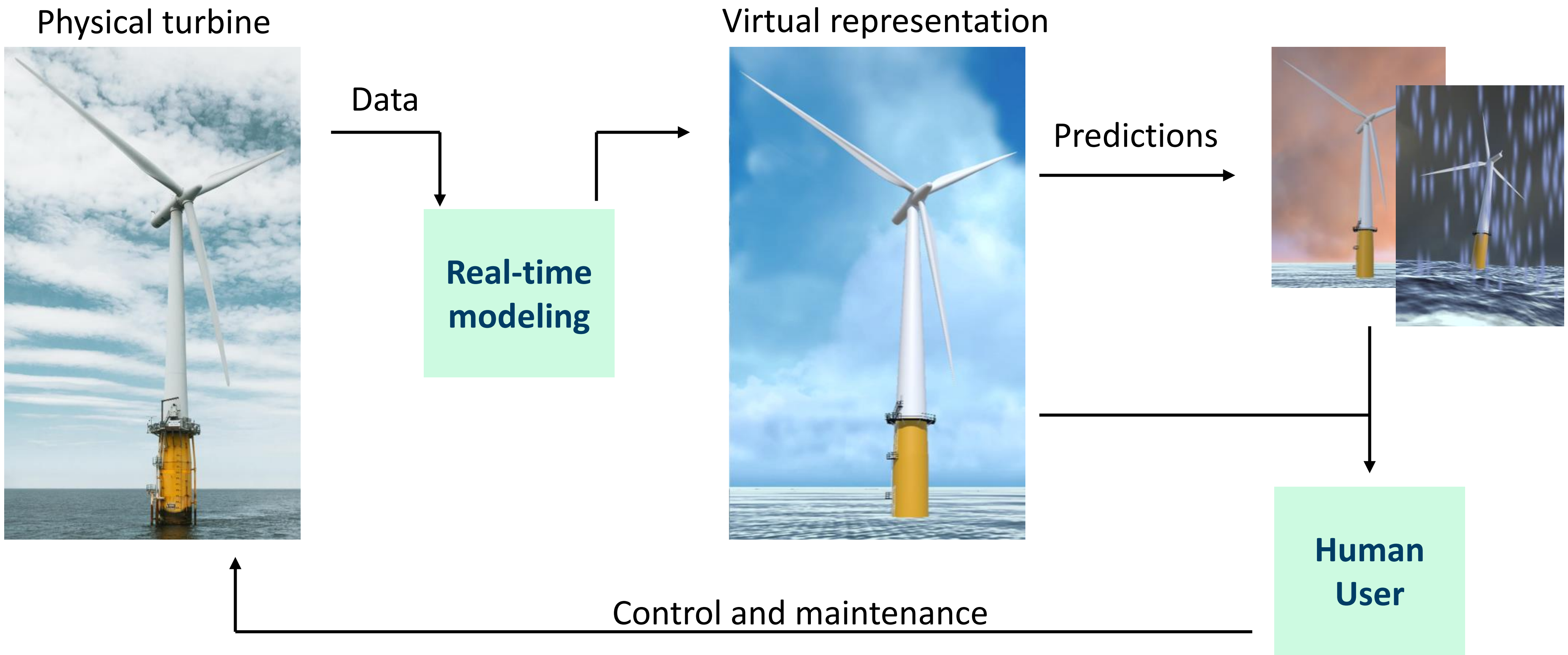

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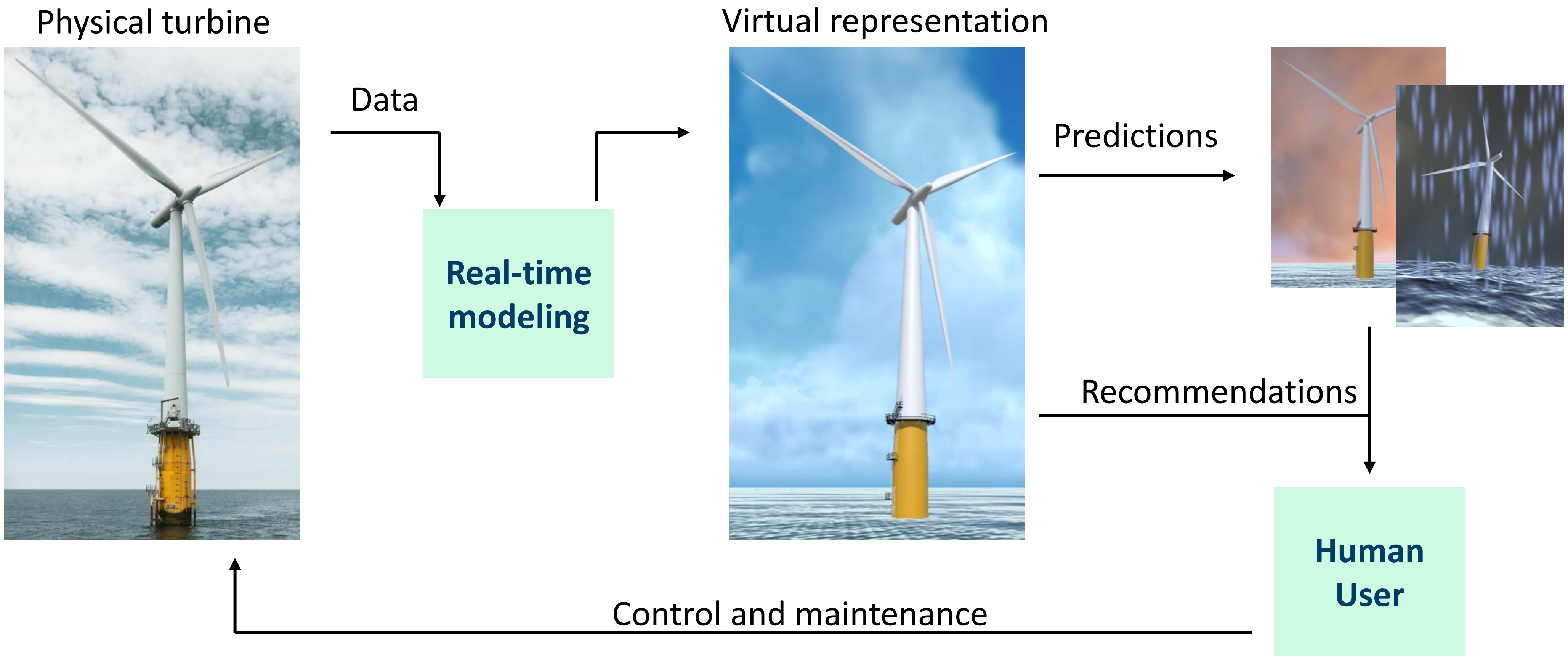

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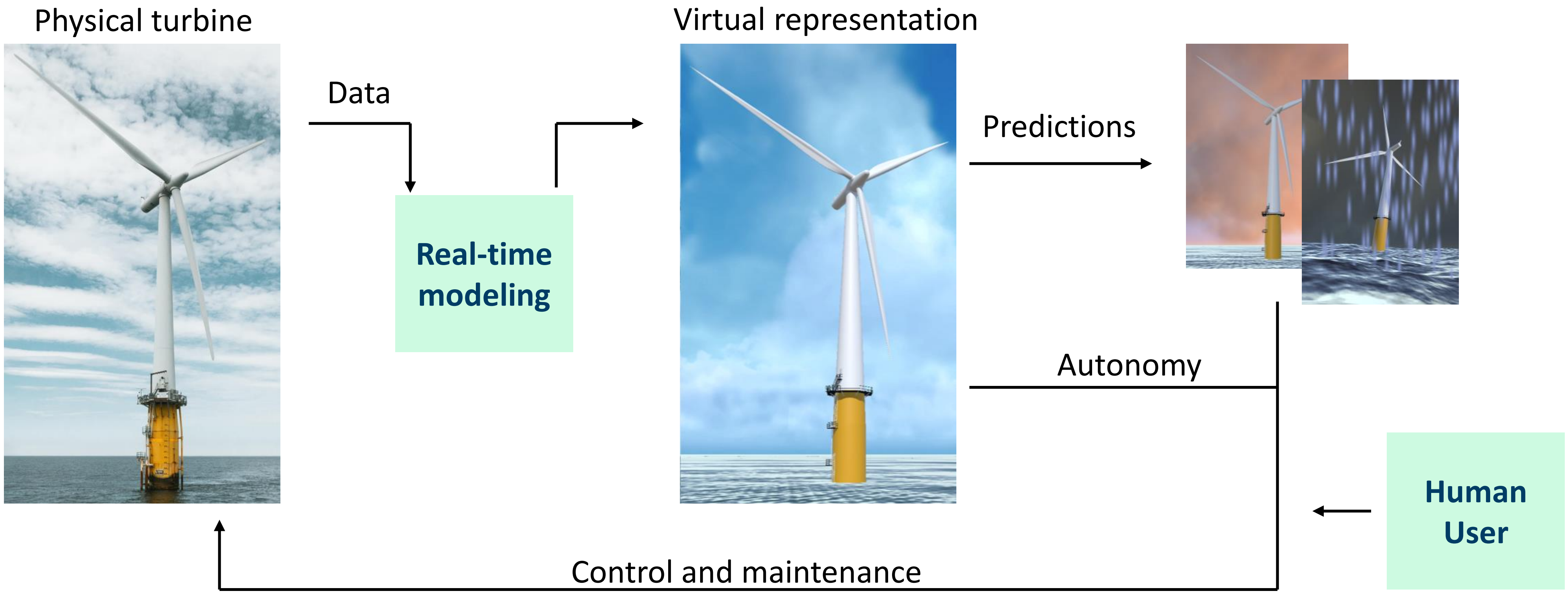

Anomaly Detection Concept

1. Measure wind speed and active power

$$u = 10 \text{ m/s}$$

$$P = 1.7 \text{ MW}$$

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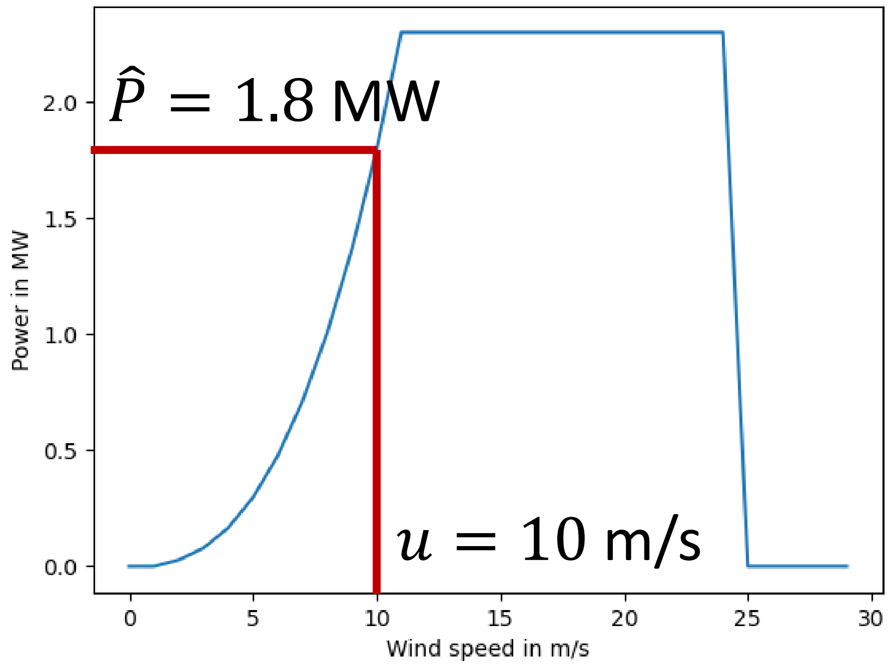
2. Infer expected power from wind speed



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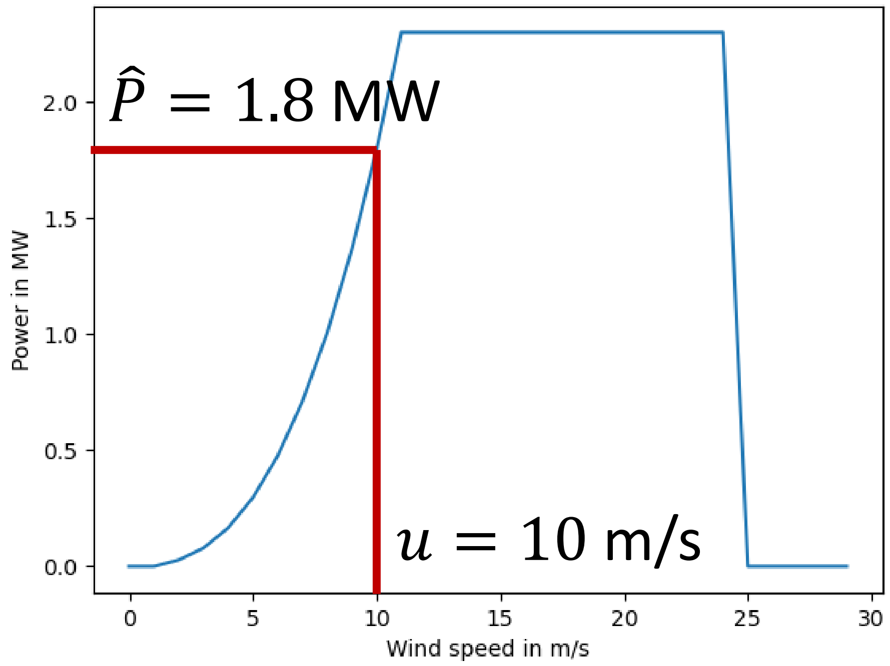


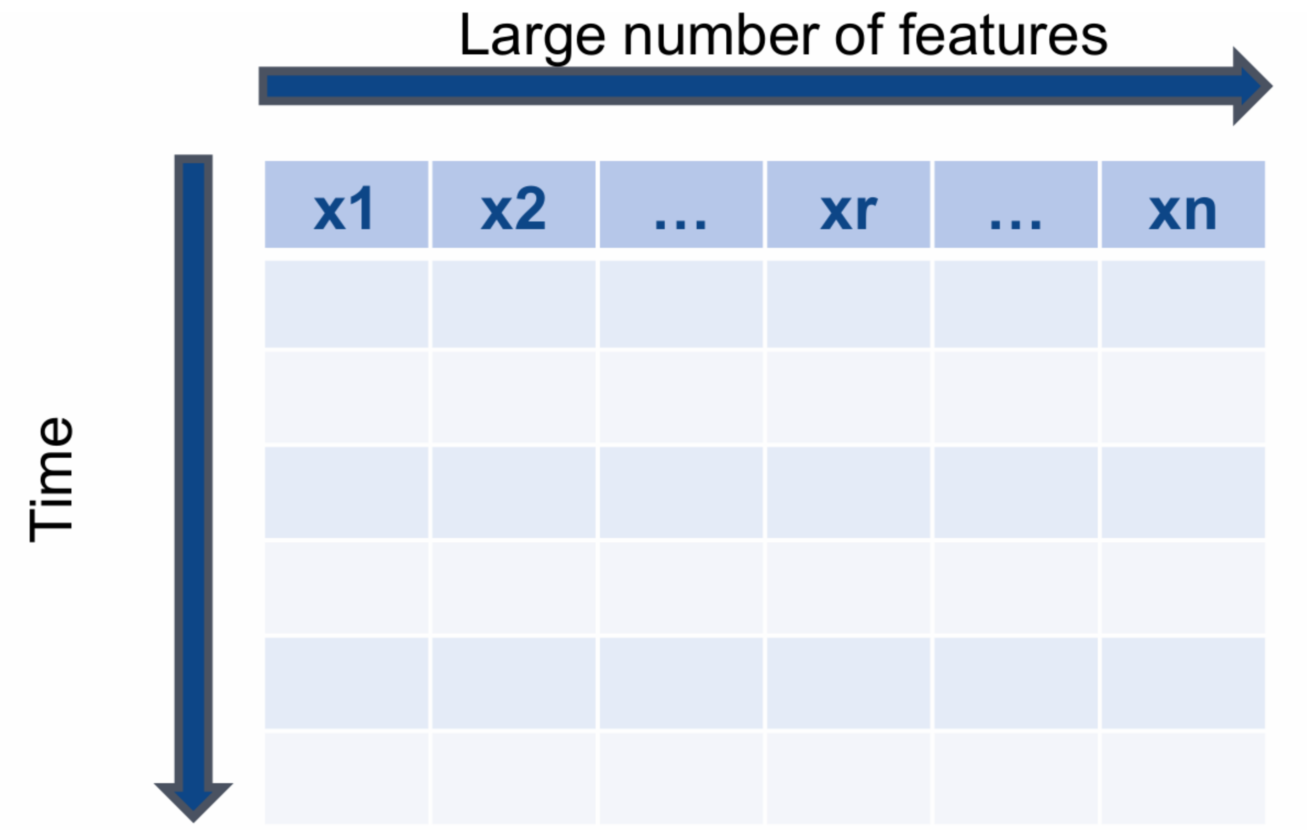
3. Compare measured power with expected power

   $P = 1.7$ MW

   $\hat{P} = 1.8$ MW

   $$\Delta P = \left|\hat{P} - P\right| = 0.1 \text{ MW}$$

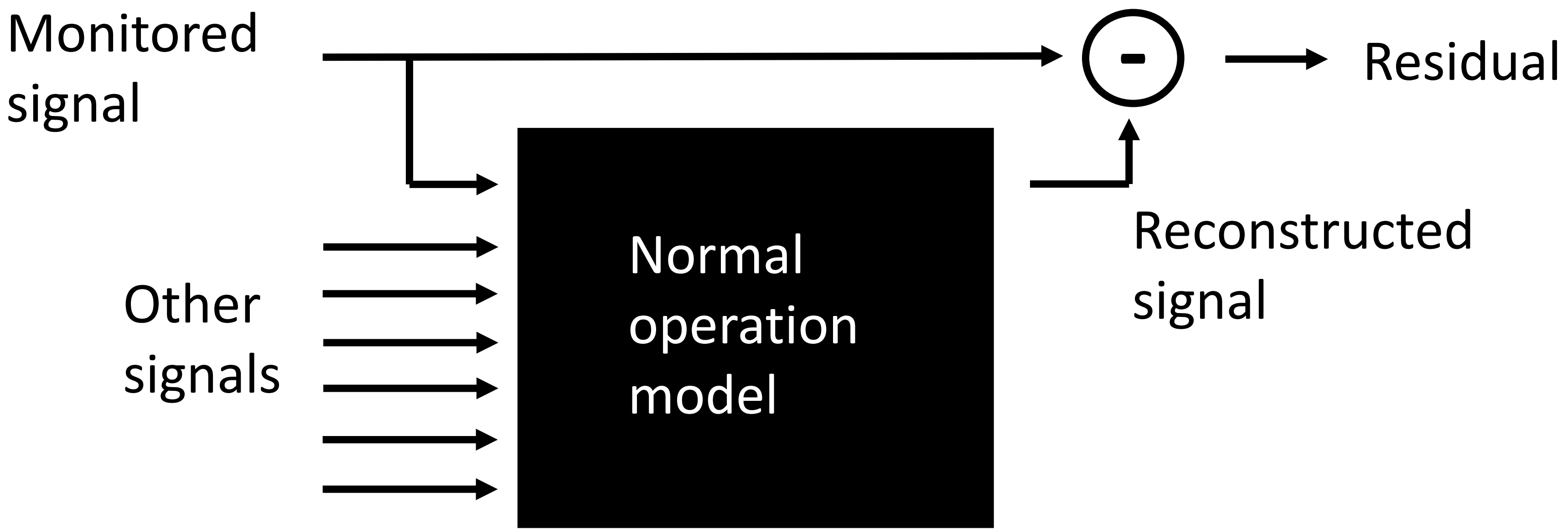
Multivariate Data analysis



Hundreds of features:

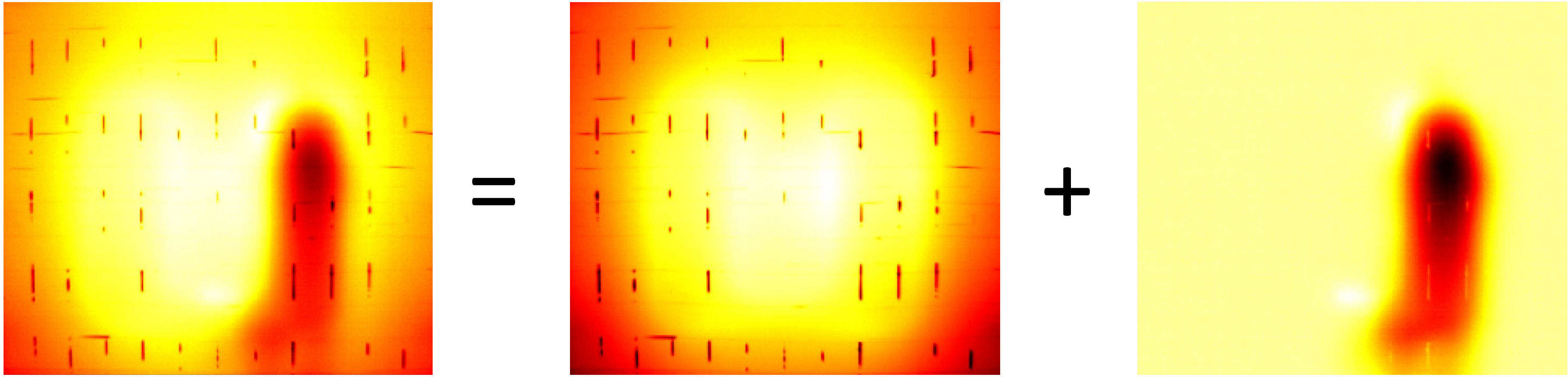
- Active power
- Main shaft RPM
- Generator RPM
- Wind speed
- Wind direction
- Nacelle direction
- Blade 1 pitch
- Blade 2 pitch
- Blade 3 pitch
- Turbine active
- Generator stator temperature
- Generator rotor temperature
- Shaft brake 1 temperature
- Shaft brake 2 temperature
- Main bearing temperature
- Oil temperature
- Turbine status
- Generator status
- Earth switch 1
- Earth switch 2
- Significant wave height
- Wave heading
- Wind gust speed
- …

Normal Operation Model



Robust Principal Component Analysis (RPCA)

Measurements (full matrix) | Basis (low-rank matrix) | Outliers (sparse matrix)



$$\underset{\mathbf{L},\mathbf{S}}{\text{minimize}} \quad \text{rank}(\mathbf{L}) + \|\mathbf{S}\|_0$$
$$\text{subject to} \quad \mathbf{L} + \mathbf{S} = \mathbf{X}$$

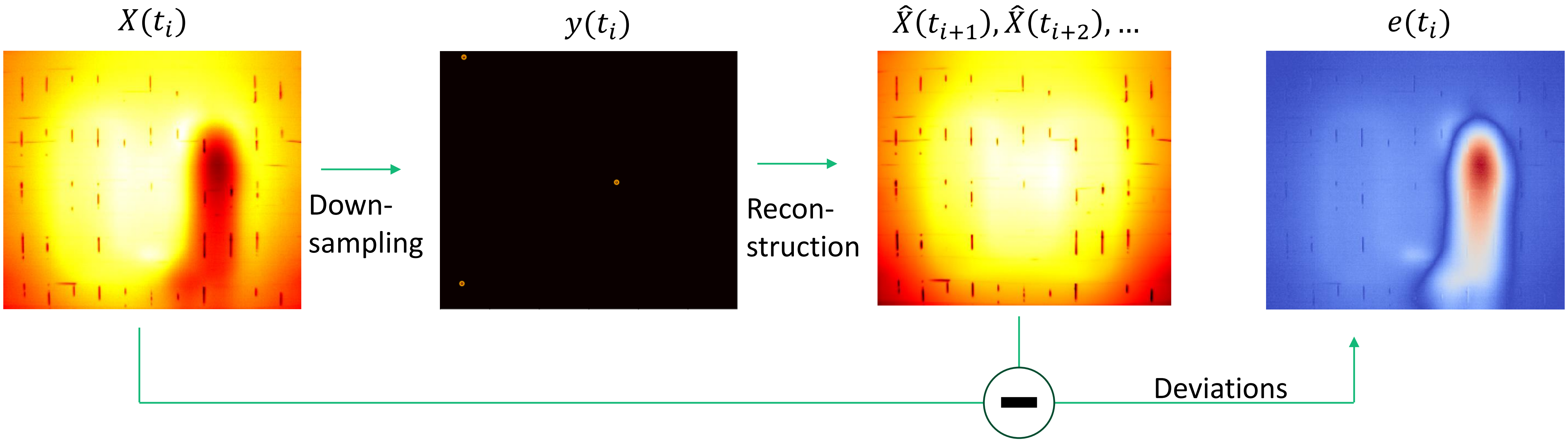
NP-hard problem (nonconvex)

$$\underset{\mathbf{L},\mathbf{S}}{\text{minimize}} \quad \|\mathbf{L}\|_* + \lambda\|\mathbf{S}\|_1$$
$$\text{subject to} \quad \mathbf{L} + \mathbf{S} = \mathbf{X}$$

Convex problem

Good for data cleaning (offline for training data)
Not real-time capable for very large data streams & window size (here ~5s)

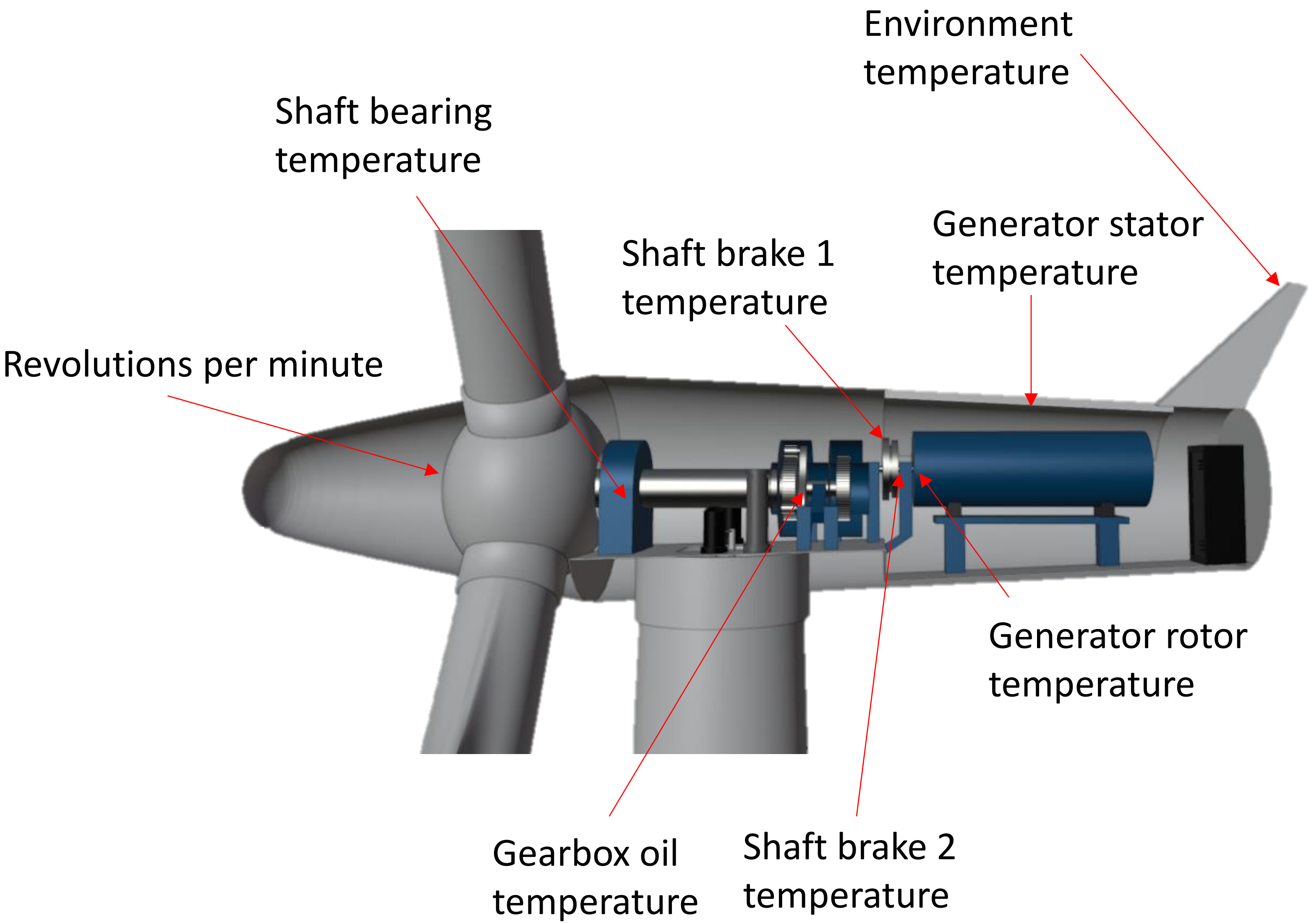
Optimal Sensing Location (OSL)



$X \approx \Psi_r a$	deconstruct x into SVD modes and time-varying coefficients
$y = CX$	measure only few sampling points
$\Psi_r = QR$	find C from QR factorization of Ψ_r
$\hat{X} = \Psi_\mathrm{r}(C\Psi_r)^T y$	reconstruct an estimate of X from y
$e = X - \hat{X}$	calculate error

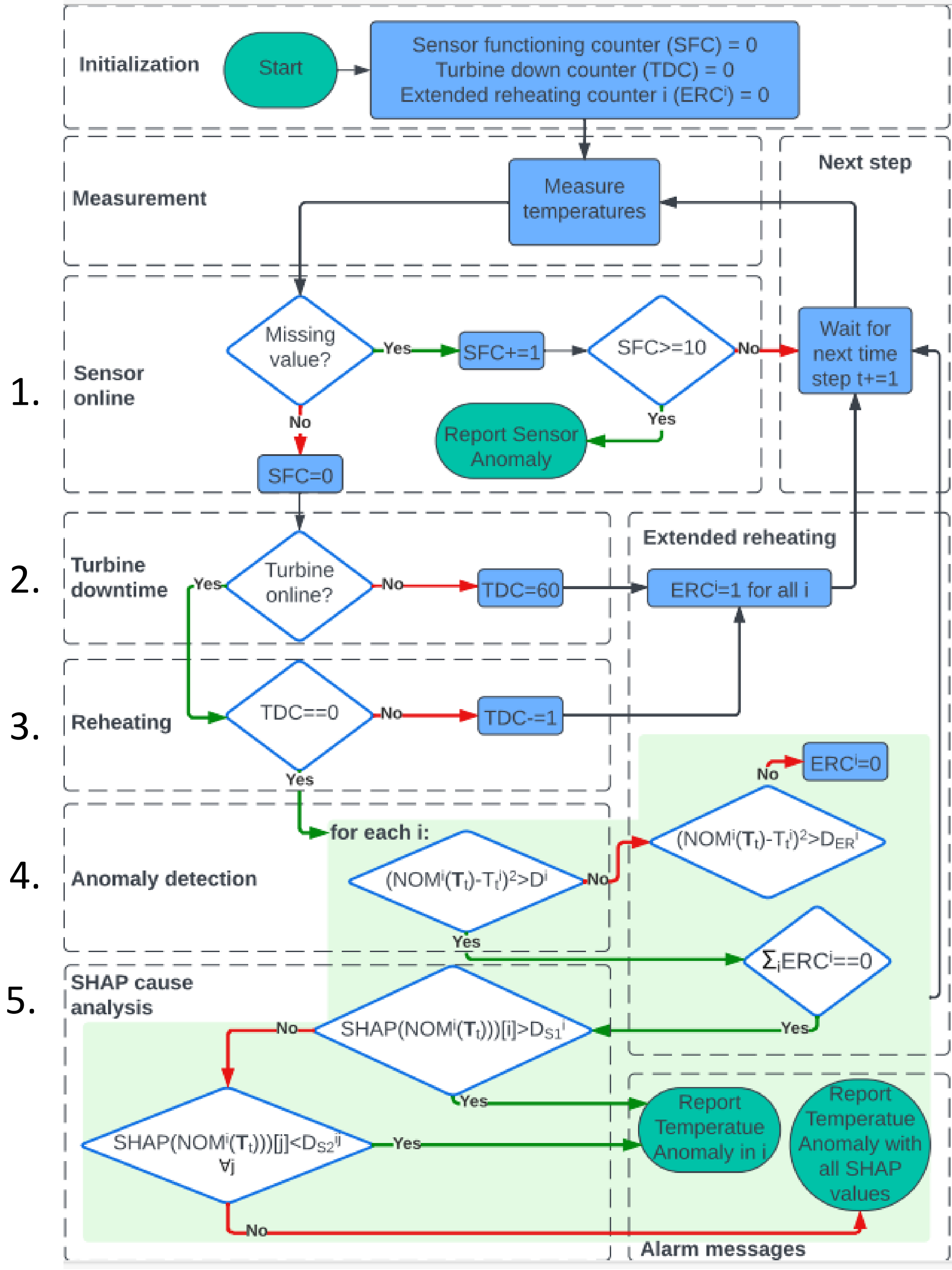
Zefyros Floating Offshore Wind Turbine

- 1 year of operational data
- 6 temperature sensors
- 2 exogenous variables
- 6 Dense neural networks



Anomaly Detection Pipeline

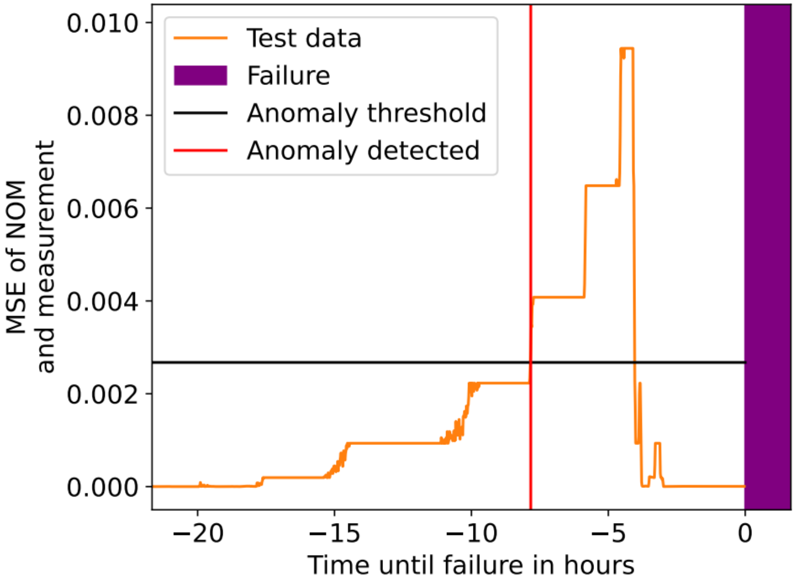
1. Sensors working?
2. Turbine online?
3. Turbine has been recently offline?
4. Anomaly in signals?
5. Which signal?



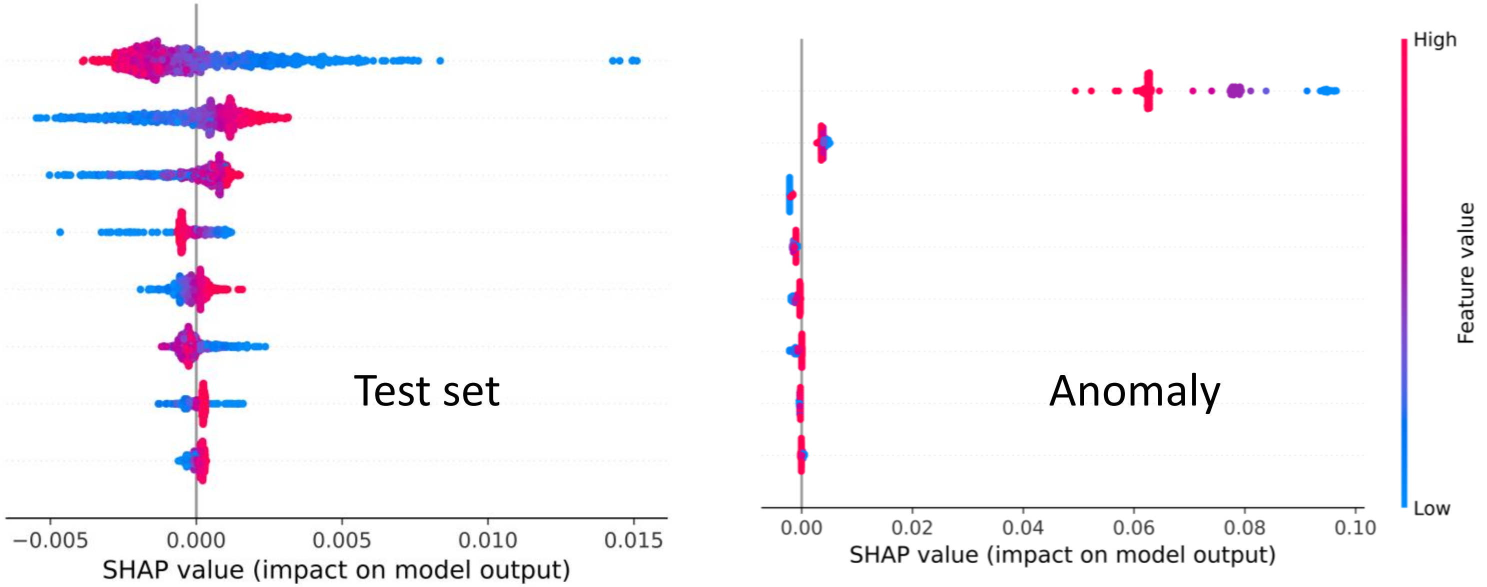
Anomaly detection on Zefyros

- Anomaly detected before fault with >99.8% probability
- Root cause identified with Shapley Additive Values

Identified Anomaly



SHAP values to identify root cause



Summary

- Digital twins have many purposes
- The capability level scale helps to classify digital twins and plan implementation
- Diagnostic digital twins are highly sought after in the industry
- Consider multivariate data analysis for anomaly detection to take advantage of correlations, such as:
  - Robust Principal Component Analysis (RPCA)
  - Optimal Sensing Location (OSL)
  - Neural network encoding/decoding + Explainable artificial intelligence

Contact:

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