Hybrid Analysis and Modeling as a Digital Twin Enabler for Wind Energy

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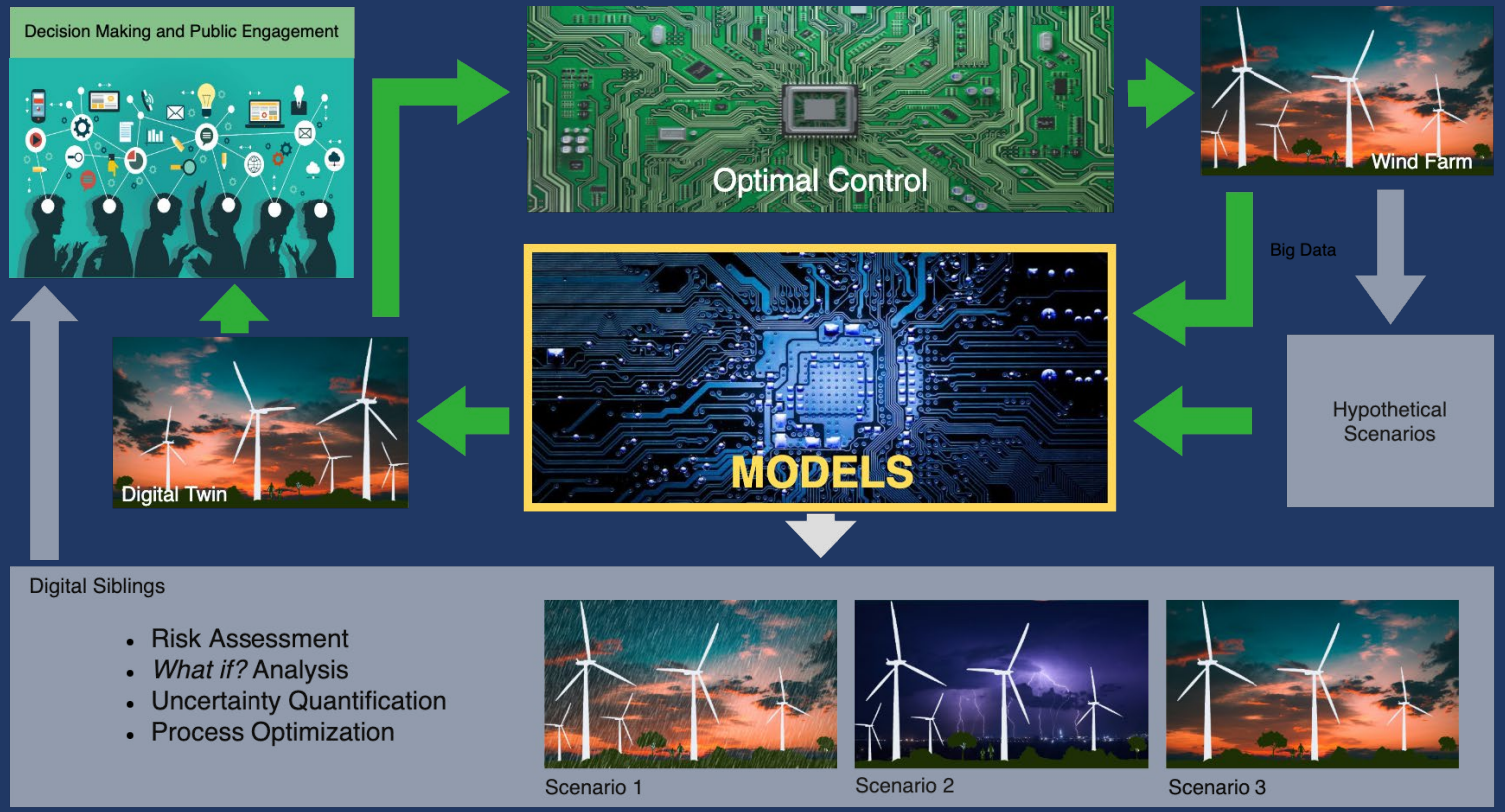


0. Standalone
Standalone description of the asset disconnected from the real environment. The physical asset may not yet exist.

2. Diagnostic
Can present diagnostic information which supports users with condition monitoring and troubleshooting.

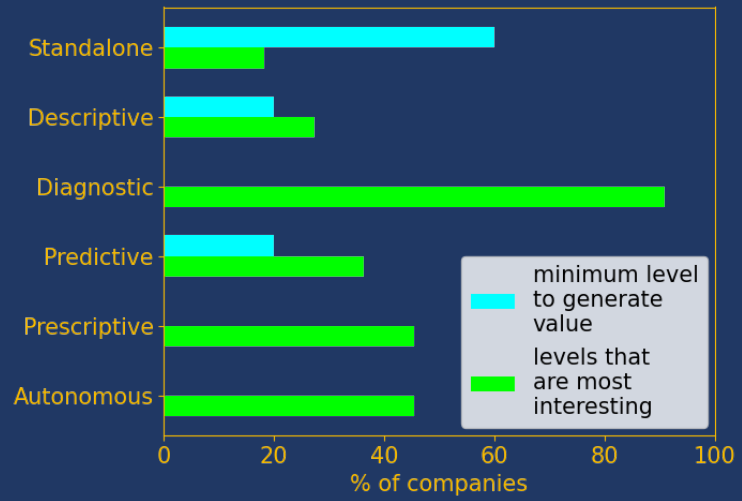
4. Prescriptive
Can provide prescription or recommendations based on what if / risk analysis and uncertainty quantification.

1. Descriptive
CAD-models and real-time stream of sensor data describe the up to date state of the asset at any point of time.

3. Predictive
Can predict the system's future states or performance and can support prognostic capabilities.

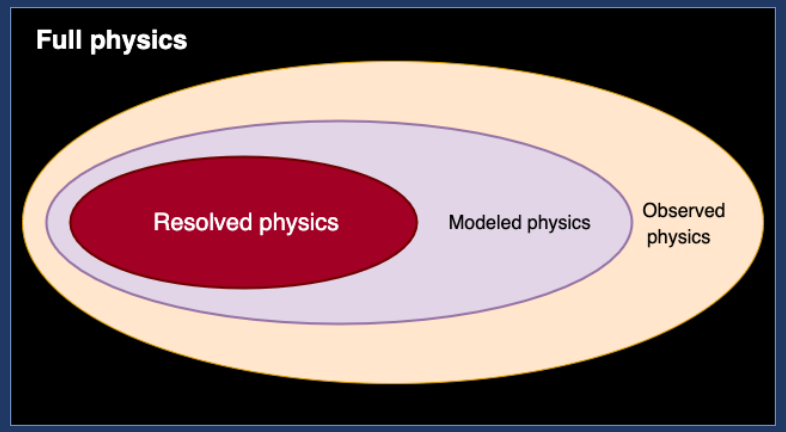
5. Autonomous
Can replace the user by closing the control loop to make decisions and execute control actions on the system autonomously.

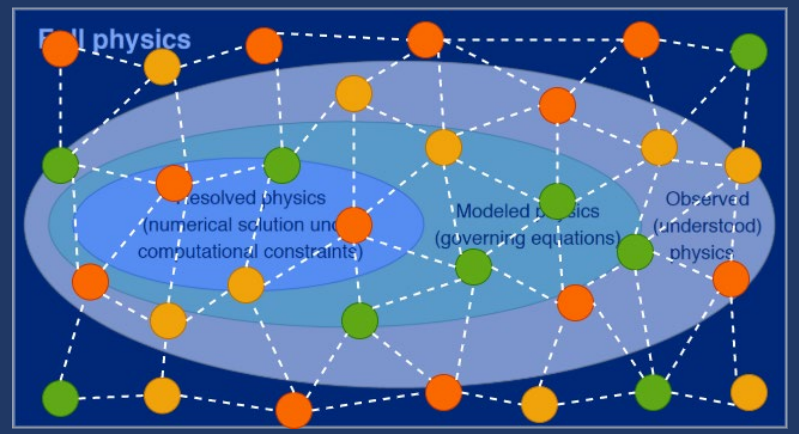
A digital twin is defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, control, and improved decision making.

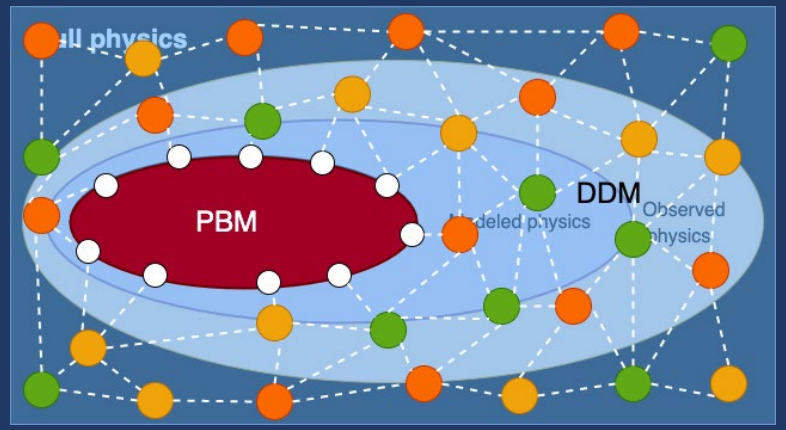


Result of a survey involving industry partners of the NorthWind project

Digital twin technology requires a paradigm shift in modeling







Physics Based Modeling

☺ Generalizable

☺ Trustworthy

☹ Computationally inefficient

☹ Static

Data Driven Modeling

☹ Non-generalizable

☹ Blackbox

☺ Computationally efficient

☺ Self-adapting

Hybrid Analysis and Modeling

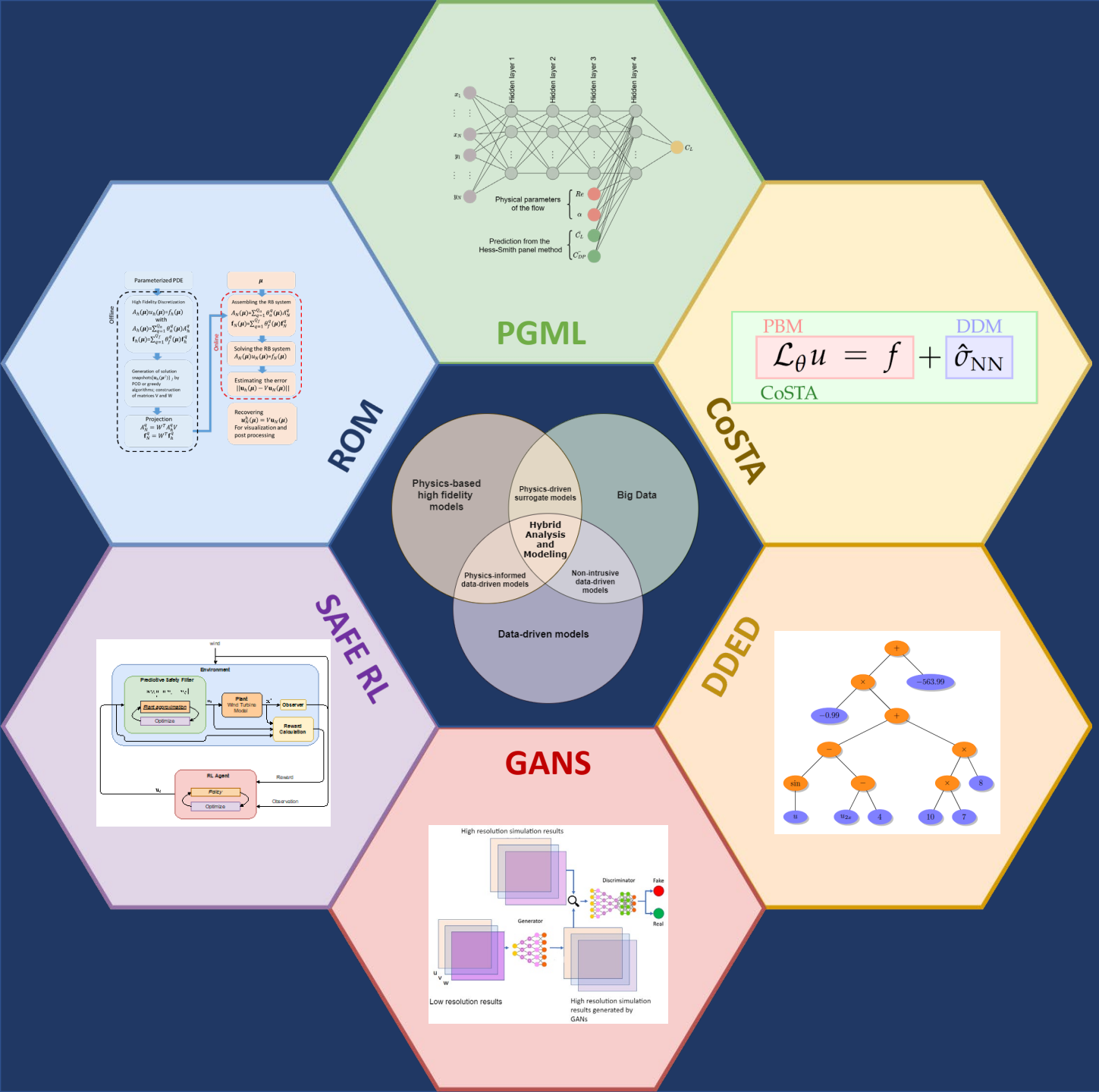
☺ Generalizable

☺ Trustworthy

☺ Computationally efficient

☺ Self-adapting

Hybrid Analysis and Modeling is defined as a modeling approach that combines the interpretability, robust foundation and understanding of a physics based modeling approach with the accuracy, efficiency, and automatic pattern-identification capabilities of advanced data-driven ML and AI algorithms.



Physics-Guided Machine Learning involves injection of partial knowledge into an intermediate layer of a neural network

Corrective Source Term Approach uses a neural network to correct a physics based model for unknown / unmodelled physics

Data Driven Equation Discovery does not require any knowledge of the first principle to derive equations / new physics

Generative Adversarial Networks can be utilized to generate high fidelity results from coarse simulations

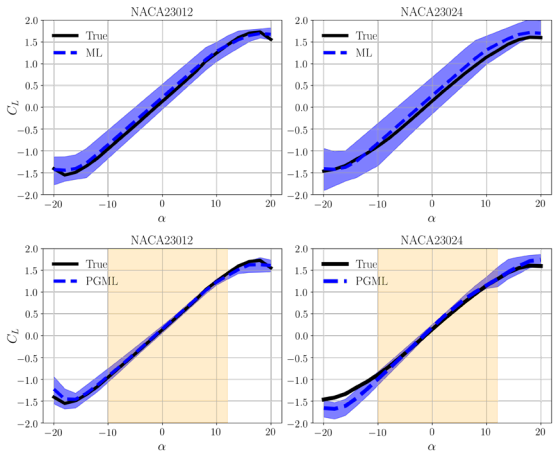
Safe Reinforcement Learning ensures safe model free control

Reduced Order Model gives online computational efficiency at the expense of expensive offline simulations

PGML

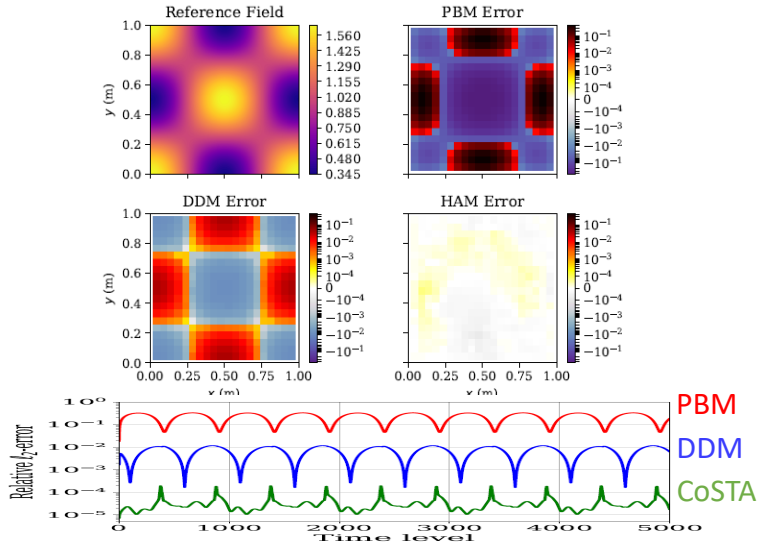
DDM

PGML



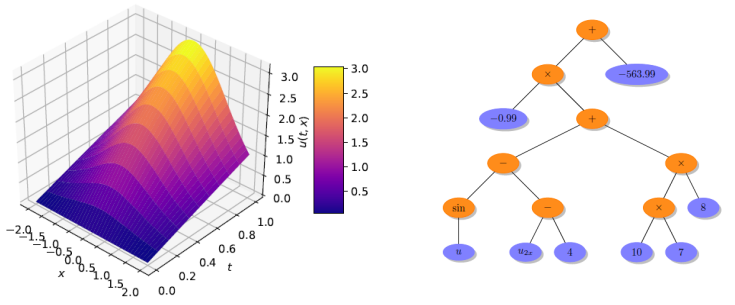
Aerodynamic characteristics of the airfoil computed using PGML

CoSTA



2D heat transfer with unknown source term modelled using CoSTA

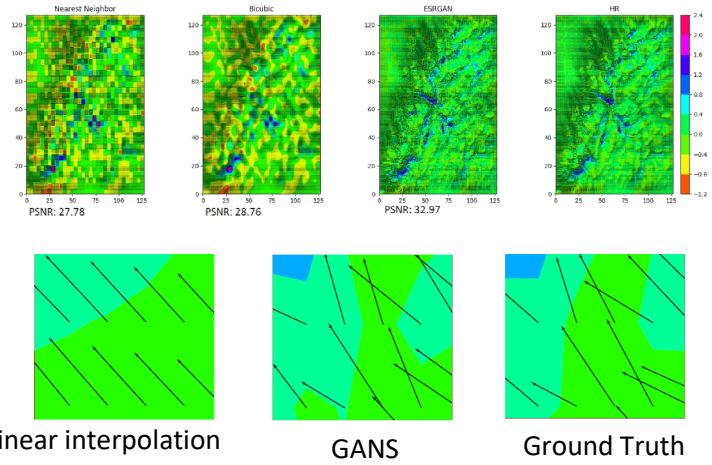
DDED



Recovered	Test error
True $u_{2t} = 1.00\ u_{2x} - 1.00\ \sin(u)$	
GEP $u_{2t} = 0.99\ u_{2x} - 0.99\ \sin(u) - 1.82 \times 10^{-5}$	1.57×10^{-4}

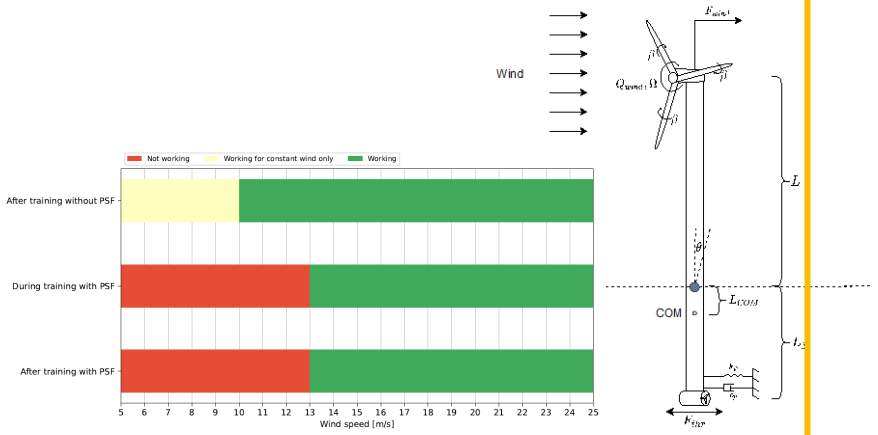
Sine-Gorden equation discovered using DDED

GANS



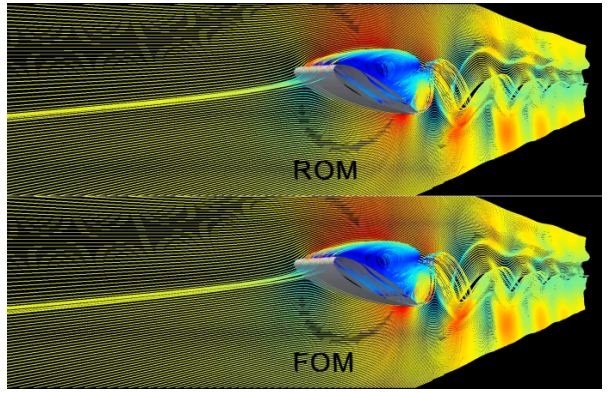
2D high resolution wind field in the Bessaker wind farm recovered from low resolution simulaiton using GANS

SAFE RL



Stabilization of a floating wind turbine using SAFE RL

ROM



Turbulent flow modeling around a 3D airfoil using ROM

HAM is accurate, certain, computaionally efficent and trustworthy, all the traits required in a modeling appraoch to instill physical realism in Digital Twins