Digital twin integrated life-cycle management of offshore wind assets via multi-agent reinforcement learning

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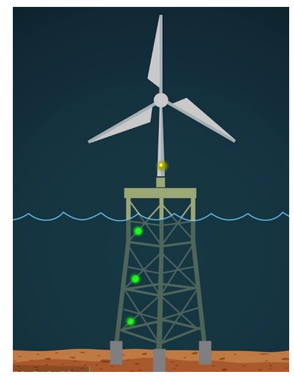
Research Objective

- ❖ To optimally allocate inspection and maintenance actions.
- ❖ To identify when the digital twin needs to be updated with new data.
- ❖ To maximize the value of SHM information.



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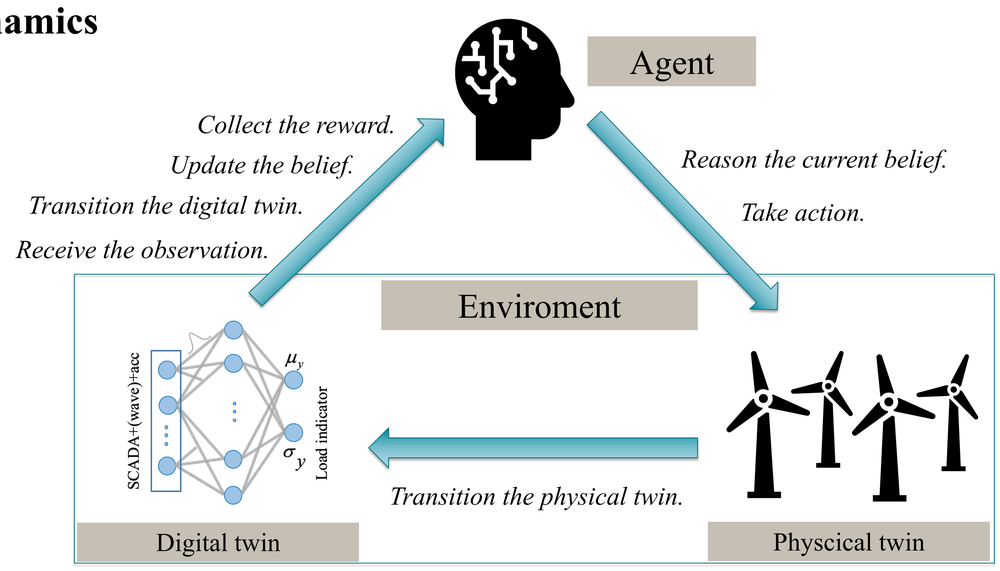
1. Digital twin integrated decision-making framework

Decentralized POMDP (multi-agent reinforcement learning) dynamics



Uncertainty propagation of digital twin

Uncertainty of virtual sensor: $\epsilon = \mathcal{N}(\mu_\epsilon, \mathrm{cov} = 0.25)$

Initial model uncertainty: $\mu_0 = 0.1$

$\epsilon_0 = \mathcal{N}(\mu_0, 0.25\mu_0)$

↓

Draw a realization: $\hat{\epsilon}_0$

↓

Generate observation matrix 'O'

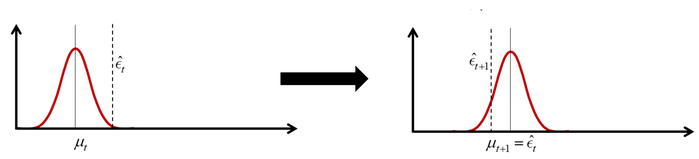
$q_{obs} = \mathcal{N}\left(q, (0.07 + \hat{\epsilon}_0).q\right)$

↓

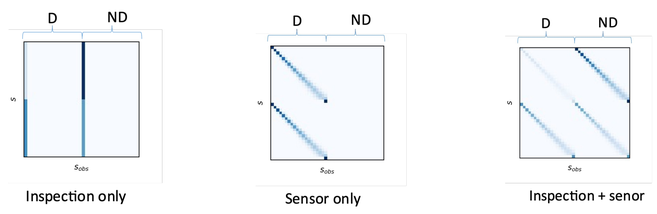
$\mu_1 = \hat{\epsilon}_0$

↓

$\epsilon_1 = \mathcal{N}(\mu_1, 0.25\mu_1)$

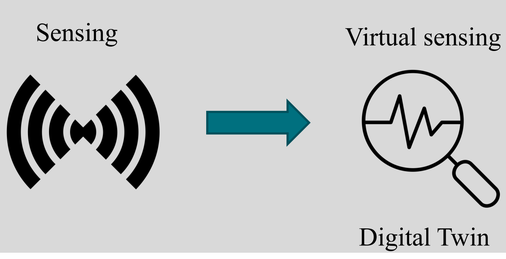


Observation probabilities 'O'

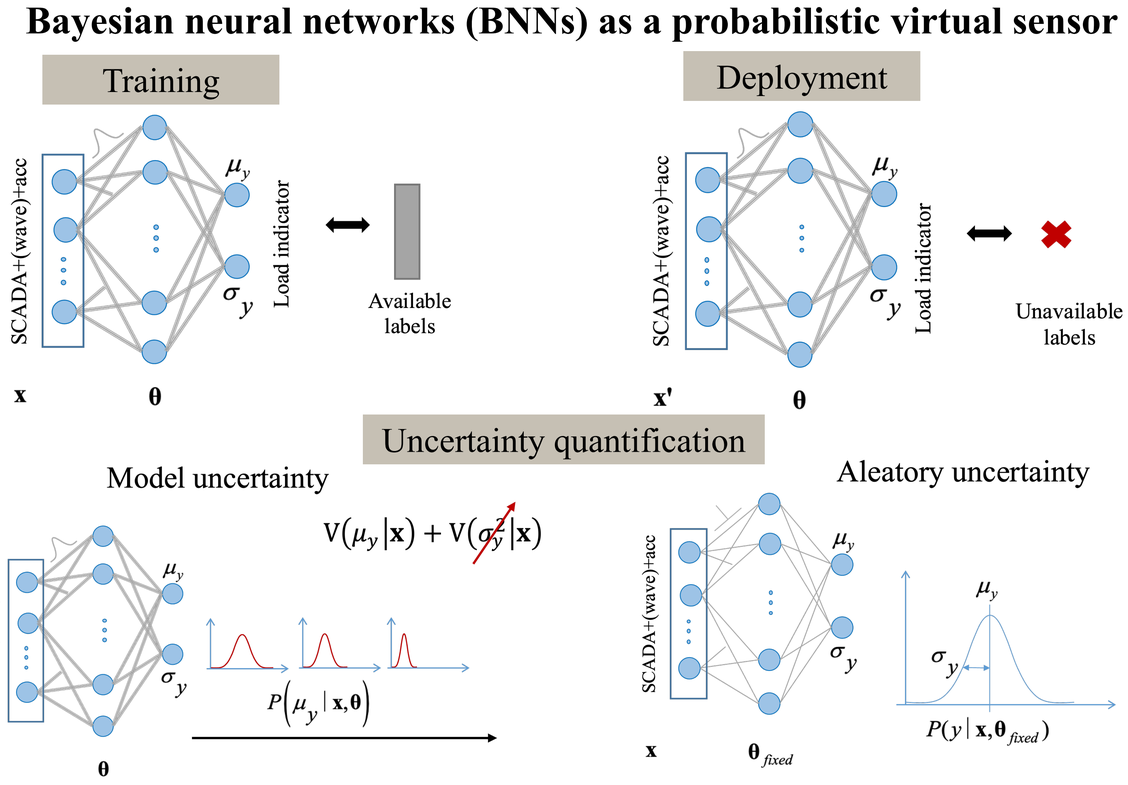


2. Virtual sensing and digital twin

- Sensors prone to damage and their lifetime being limited.
- Advancement of artificial intelligence and machine learning tools.

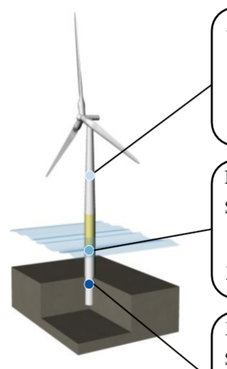


Bayesian neural networks (BNNs) as a probabilistic virtual sensor



NOTE: The implementation of the BNN-powered virtual monitoring frameworkis available on the github repository https://github.com/Nandarhline/BayesianNN

3. Life-cycle management of an OW sub-structure



AW: $FDF = 1$; $d_{crit} = 20$ mm
SN curve in air
$q \sim \mathcal{N}[\mu = 10.21, CoV = 25\%]$
$\ln(C_{FM}) \sim \mathcal{N}[\mu = -26.45, \sigma = 0.12]$

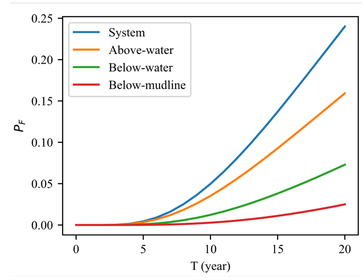
BW: $FDF = 2$; $d_{crit} = 60$ mm
SN curve in seawater - cathodic prot.
$q \sim \mathcal{N}[\mu = 7.40, CoV = 25\%]$
$\ln(C_{FM}) \sim \mathcal{N}[\mu = -26.04, \sigma = 0.40]$

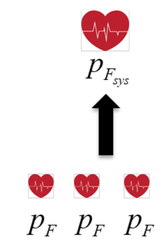
MD: $FDF = 3$; $d_{crit} = 60$ mm
SN curve in seawater - cathodic prot.
$q \sim \mathcal{N}[\mu = 6.74, CoV = 25\%]$
$\ln(C_{FM}) \sim \mathcal{N}[\mu = -26.12, \sigma = 0.39]$

Deterioration model:

$$d_{t+1} = \left[d_t^{\frac{2-m}{2}} + \left(\frac{2-m}{2}\right) C_{FM} \{S_R \pi^{0.5}\}^m n \right]^{\frac{2}{2-m}}$$

Unconditional failure probability:

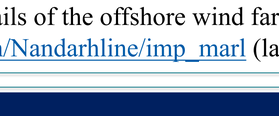




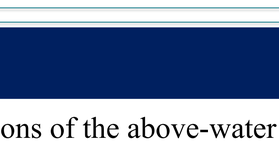
States and transition models

Physical twin

Crack size (30 states)



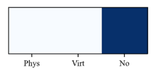
Scale parameter of stress range distribution (20 states)



Deterioration rate

Digital twin

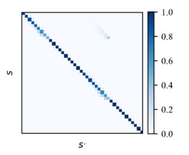
Presence of physical sensor or virtual sensor (digital twin)
- Physical sensor
- Virtual sensor
- No sensor



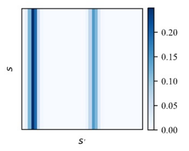
Model uncertainty of virtual sensor
- Mean and CoV

0.1	0.25

T_0
- Do-nothing
- Inspection
- Install-sensor
- Inspection/Install-sensor



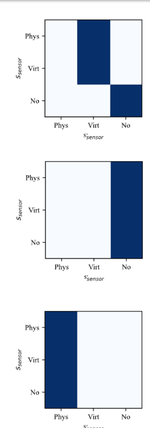
T_r
- Perfect-repair
- Perfect-repair/Install-sensor



T_{0twin}
- Do-nothing
- Inspection

T_{rtwin}
- Perfect-repair

T_{stwin}
- Install-sensor
- Inspection/Install-sensor
- Perfect-repair/Install-sensor



NOTE: More details of the offshore wind farm + digital twin environment are available on the github repository https://github.com/Nandarhline/imp_marl (later will be merged to https://github.com/moratodpg/imp_marl)

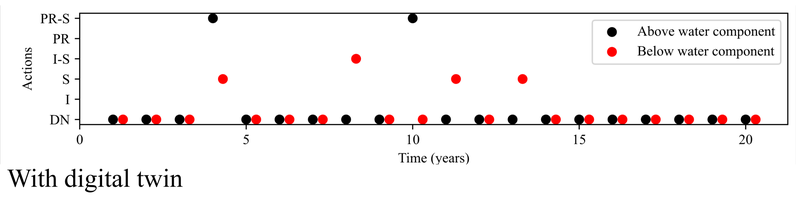
4. Results

Policy realizations of the above-water and below-water components:

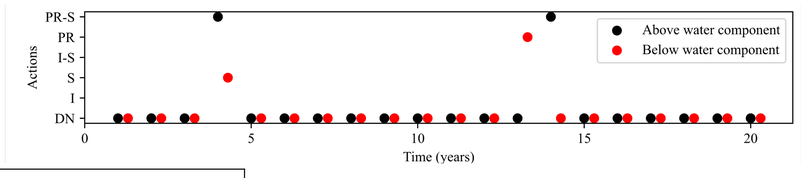
Actions:

- Do nothing (DN)
- Inspection (I)
- Install sensor (S)
- Insepction and install sensor (I-S)
- Perfect repair (PR)
- Perfect repair and install sensor (PR-S)

Without digital twin



With digital twin



	Expected life-cycle cost (monetary units)
Without digital twin	157
With digital twin	145

Value of information from digital twin:

VOI = 12 monetary units
(note: 1 inspection costs 1 monetary unit)

Conclusions

- We can maximize the value of SHM information by integrating virtual sensing via digital twin.
- The multi-agent reinforcement learning framework will automatically notify when the digital twin needs to be updated.

Offshore Wind PhD Day
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