CORTEX

Core monitoring techniques and experimental validation and demonstration

# Deep Learning-based Anomaly Detection in Nuclear Reactor Cores

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# Overview

- The introduction of a deep learning methodology for the classification of different perturbation types and their position in the reactor core, using convolutional neural networks
- The performance of a complementary robustness analysis to assess the system's performance on noisy or missing data
- The assessment of the system's functionality on plant measurements obtained from the Gösgen nuclear power plan in Switzerland

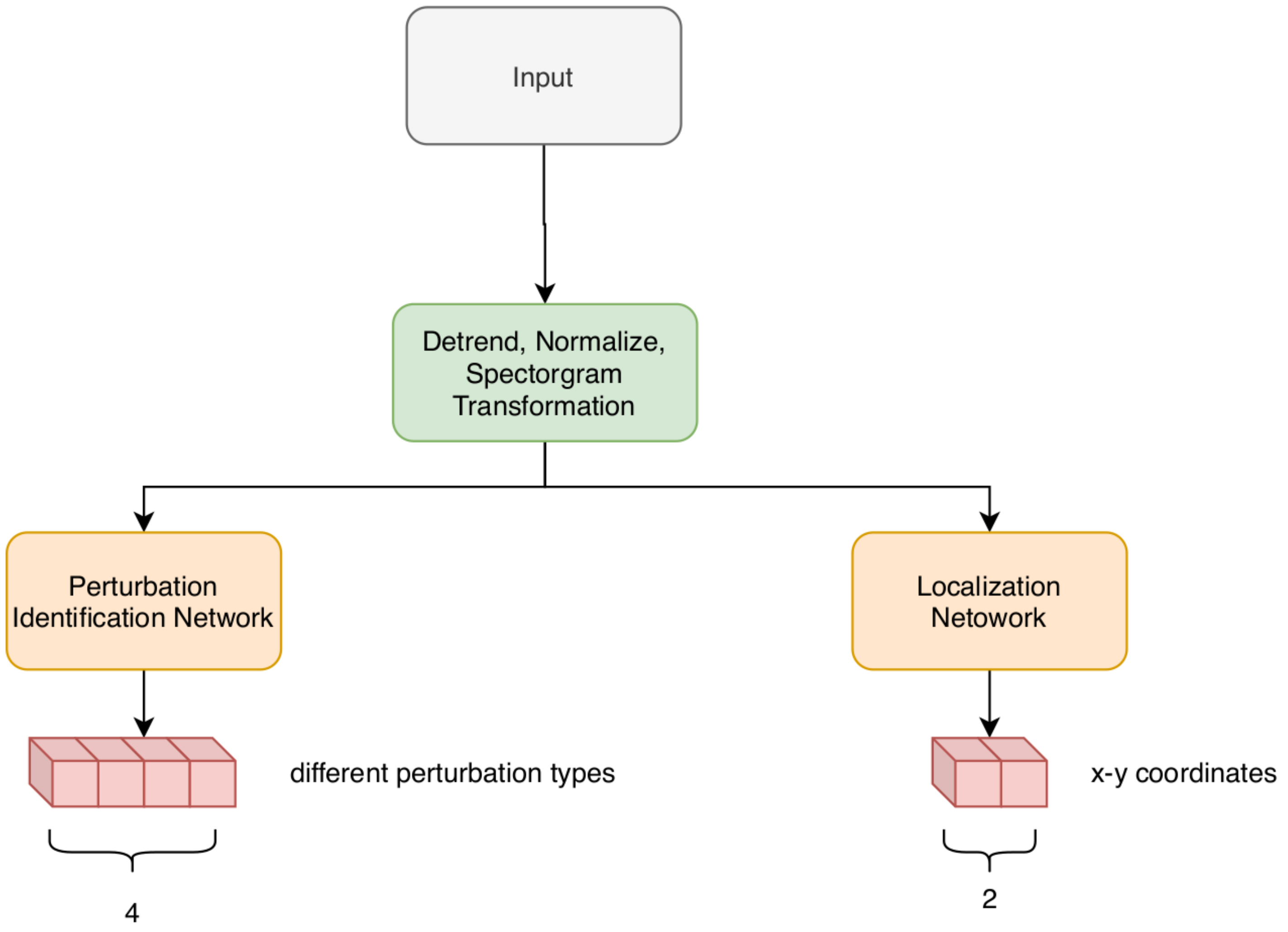
# Noise analysis

- Assess the condition of the reactor core using noise diagnostics
  - Measure the fluctuation of neutron flux around a mean value using in-core & ex-core detectors
- Type & number of perturbations occurring in the core is usually unknown
- Modelling techniques allow for the simulation of perturbations in the core
  - Estimate the induced neutron flux in the core for known, realistic perturbations
- The deep learning architecture <u>learns</u> the patterns of the simulated perturbations…
- … and tries to determine whether they occur in actual plant measurements

# Simulated measurements

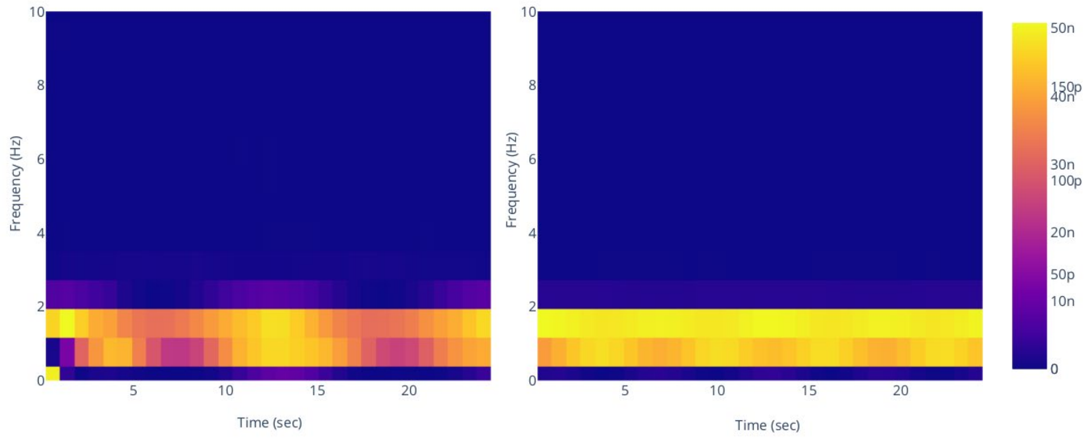
- Performed for a Swiss pre-KONVOI pressurized water reactor
  - 3-loop reactor, 177 fuel assemblies
- Neutron noise simulations based on the CASMO-5 SIMULATE-3 code system, coupled with the SIMULATE-3K transient nodal code
- Type of perturbations
  - Individual fuel assembly vibrations
    - Cantilevered, C-shape and S-shaped modes
  - Inlet coolant temperature fluctuations
  - Inlet coolant flow fluctuations
  - ... and their combinations

# The proposed architecture at a glance

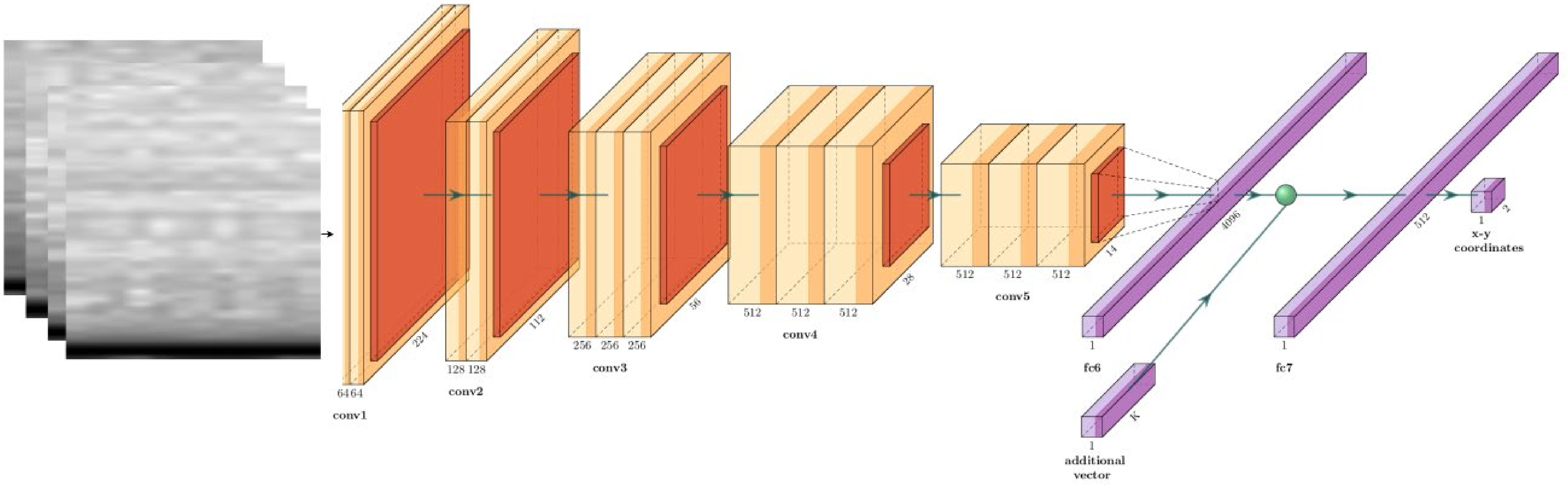


# System input

- Input is a transformed version of the initial detector signal
- Input is detrended and normalized
- Time domain signals are transformed into scaleograms, based on the wavelet transform



# ResNet architecture (identification & localization networks)



# Identification task results

**F1-score of the perturbation identification network for varying SNR ratios**

| **Perturbation type** | **SNR=**10 | **SNR=**1 | **SNR=**0.1 | **SNR=**0.01 |
|---|---|---|---|---|
| FA vibration | 1.00 | 1.00 | 0.99 | 0.17 |
| Inlet temperature fluctuation | 1.00 | 0.99 | 0.53 | 0.30 |
| Inlet flow fluctuation | 1.00 | 1.00 | 0.62 | 0.09 |
| Cluster vibration & thermohydraulical fluctuation | 0.99 | 0.99 | 0.66 | 0.30 |

# Localization task results

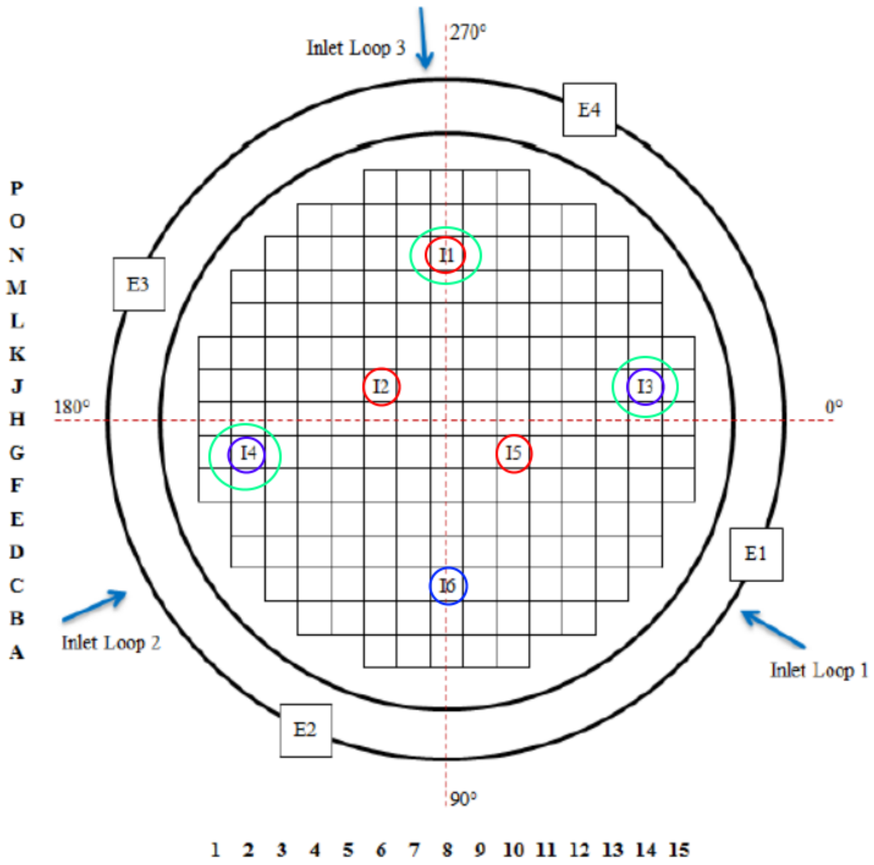
Only for the fuel assembly vibration case

**Prediction accuracy of the localization network**

| Prediction proximity | Proportion of the test set |
|---|---|
| exact | 0.73 |
| 1 difference | 0.21 |
| $> 1$ difference | 0.06 |

# Robustness Analysis: faulty detectors

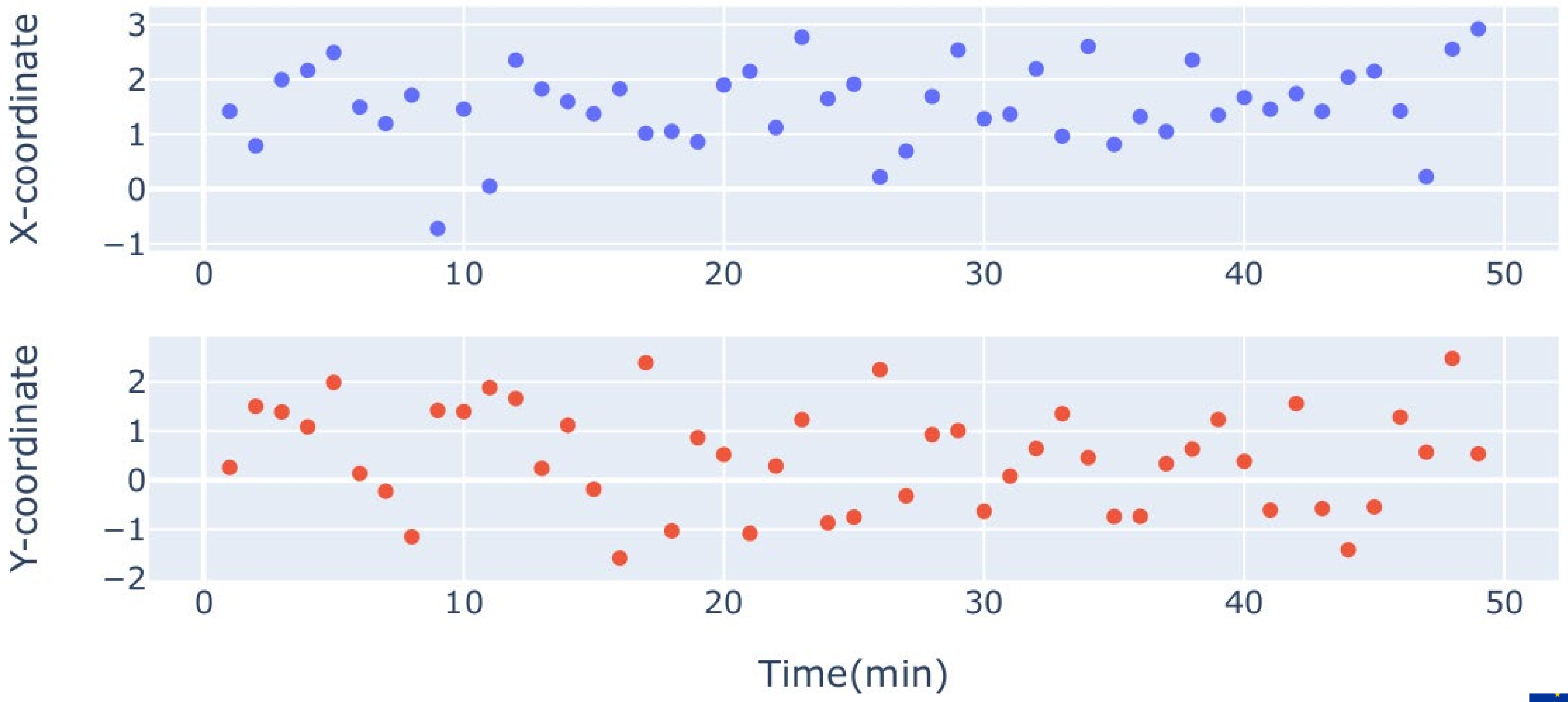
- Assess the distinguising capability of the models, given partial information about grid condition
- Create subsets of functional in-core & ex-core detectors



## Prediction accuracy of the localization network for different subsets of functional detector signals

| | Functional subsets of detectors | | | | | |
|---|---|---|---|---|---|---|
| Prediction proximity | $I_1, I_2, I_5$ | $I_1, I_2, I_5$ + ex-core | $I_3, I_4, I_6$ | $I_3, I_4, I_6$ + ex-core | $I_1, I_3, I_4$ | $I_1, I_3, I_4$ + ex-core |
| exact | 0.52 | 0.58 | 0.48 | 0.65 | 0.43 | 0.66 |
| 1 difference | 0.31 | 0.32 | 0.32 | 0.26 | 0.34 | 0.22 |
| 2 difference | 0.11 | 0.07 | 0.13 | 0.07 | 0.15 | 0.09 |
| $>$ 2 difference | 0.06 | 0.03 | 0.07 | 0.02 | 0.08 | 0.03 |

# Preliminary comparison with plant measurements



# Thank you! Any questions?