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 learns 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

<table>
<thead>
<tr>
<th>Perturbation type</th>
<th>SNR=10</th>
<th>SNR=1</th>
<th>SNR=0.1</th>
<th>SNR=0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA vibration</td>
<td>1.00</td>
<td>1.00</td>
<td>0.99</td>
<td>0.17</td>
</tr>
<tr>
<td>Inlet temperature fluctuation</td>
<td>1.00</td>
<td>0.99</td>
<td>0.53</td>
<td>0.30</td>
</tr>
<tr>
<td>Inlet flow fluctuation</td>
<td>1.00</td>
<td>1.00</td>
<td>0.62</td>
<td>0.09</td>
</tr>
<tr>
<td>Cluster vibration &amp; thermohydraulical fluctuation</td>
<td>0.99</td>
<td>0.99</td>
<td>0.66</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Localization task results

Only for the fuel assembly vibration case

Prediction accuracy of the localization network

<table>
<thead>
<tr>
<th>Prediction proximity</th>
<th>Proportion of the test set</th>
</tr>
</thead>
<tbody>
<tr>
<td>exact</td>
<td>0.73</td>
</tr>
<tr>
<td>1 difference</td>
<td>0.21</td>
</tr>
<tr>
<td>&gt; 1 difference</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Robustness Analysis: faulty detectors

• Assess the distinguishing 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**

<table>
<thead>
<tr>
<th>Prediction proximity</th>
<th>$I_1, I_2, I_5$</th>
<th>$I_1, I_2, I_5$ + ex-core</th>
<th>$I_3, I_4, I_6$</th>
<th>$I_3, I_4, I_6$ + ex-core</th>
<th>$I_1, I_3, I_4$</th>
<th>$I_1, I_3, I_4$ + ex-core</th>
</tr>
</thead>
<tbody>
<tr>
<td>exact</td>
<td>0.52</td>
<td>0.58</td>
<td>0.48</td>
<td>0.65</td>
<td>0.43</td>
<td>0.66</td>
</tr>
<tr>
<td>1 difference</td>
<td>0.31</td>
<td>0.32</td>
<td>0.32</td>
<td>0.26</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td>2 difference</td>
<td>0.11</td>
<td>0.07</td>
<td>0.13</td>
<td>0.07</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>&gt; 2 difference</td>
<td>0.06</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
<td>0.08</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Preliminary comparison with plant measurements
Thank you! Any questions?