Condition-Based Maintenance Modelling and Decision Making taking into account Uncertainties

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Context of the Research

- Planned Maintenance approaches:
  - Scheduled Maintenance (SM)
  - Condition-Based Maintenance (CBM)
Context of the Research

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Context of the Research

- **Planned Maintenance approaches:**

  - **Scheduled Maintenance (SM)**
  - **Condition-Based Maintenance (CBM)**
• Planned Maintenance approaches:

- Scheduled Maintenance (SM)
- Condition-Based Maintenance (CBM)
Condition Based Maintenance System

Automatic-based

Alarm System Interface

Human-based

Component

Temperature ($T$)

Pressure ($P$)

Fault Detection System

Measurements

Temperature ($T$)

Pressure ($P$)

Normal Condition

Abnormal Condition

Maintenance Decision

Human- based

Maintenance

Maintenance Action

Uncertainty

Operator

No Maintenance

Sameer Al-Dahidi
An objective of the INNHF project

- Integrated framework for Condition-based Maintenance modelling and decision making taking into account uncertainties.

### Automatic-based

- Temperature \((T)\)

### Alarm System Interface

- Normal Condition
- Abnormal Condition

### Human-based

- Operator
- Maintenance Decision
- Maintenance Action

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**Uncertainty**
An objective of the INNHF project

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<table>
<thead>
<tr>
<th>Component</th>
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<th>Pressure (P)</th>
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<td>Measurements</td>
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<td></td>
</tr>
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</table>

Automatic- based | Alarm System Interface | Human- based |

Fault Detection System

Uncertainty
Model based Fault Detection System

MEASURED SIGNALS

Temperature (T) → t

Pressure (P) → t

SIGNAL RECONSTRUCTIONS

Temperature (T) → t

Pressure (P) → t

COMPARISON

NORMAL CONDITION
(Measurements = Reconstructions)

ABNORMAL CONDITION
(Measurements ≠ Reconstructions)
Sources of Uncertainty

MEASURED SIGNALS

Source 1: Uncertainty in signal measurements.

Source 2: Intrinsic stochasticity of the plant processes.

SIGNAL RECONSTRUCTIONS

Source 3: Uncertainty in Signal Reconstruction Model parameters.

Source 4: Incompleteness of training data (Empirical Models).

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ABNORMAL CONDITION
(Measurements ≠ Reconstructions)
Auto-associative Kernel Regression (AAKR)

- Historical measurements
- Test measurement
- Reconstruction
Quantification of the Uncertainty on the AAKR Reconstructions

Prediction Intervals Estimation
Prediction Interval: Desiderata

Small missed alarm rate

Small width of PIs

α% Coverage Level

Small false alarm rate

Coverage = 70%

Reconstruction based on AAKR $\hat{x}$

Test measurements $x$

Prediction Interval
$Y_1(t,\text{signal},\text{trans}) = 2^\times (a^\times (1 + \text{erf}((t-mu)/\sqrt{2}))) + 10^{-3} \times \text{rum(\text{trans}).data(t,\text{signal})}$
Prediction Intervals (PIs)

\[ \hat{\chi}^{\text{Lower,Upper}} = \hat{\chi} \pm t_{N}^{\alpha/2} \sqrt{\text{Var} \left( \hat{\chi}_{n=1,..NP} \right) + \sum_{n=1}^{NP} \left( \hat{\chi}_{n} - x_{n} \right)^{2} / NP} \]

The Student's t-distribution where \( N \) is the number of training patterns and \( \alpha \) is 5% (usually \( \approx 2 \))

LIMITATIONS:
1. Constant PIs for all measurements
2. Very large PIs for all measurements
Using Order Statistics (OS)

\[
\hat{x}_{u,l}^{n} (t) = \hat{x} (t) \pm \alpha^{95 \text{ percentile}} \sqrt{\text{Var} \left( \hat{x}_{n, \ldots, NV = 59} (t) \right) + \sum_{n=1}^{NV=59} \left( \hat{x}_{n} (t) - x_{n} (t) \right)^2 / (NV = 59)}
\]

For Variable PI

For PI Width

Using Order Statistics (OS)

What is the Scale Factor (\(\alpha\))?

Scale factor deals with the uncertainty of the AAKR model

If MSE is Small \(\rightarrow\) \(\alpha\) is Small

If MSE is Large \(\rightarrow\) \(\alpha\) is Large

<table>
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<tr>
<th>Reconstruction based on AAKR (\hat{x})</th>
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<tbody>
<tr>
<td>Historical measurement (x_n)</td>
</tr>
<tr>
<td>Test measurements (x)</td>
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<td>Prediction Interval</td>
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Variable and Narrow PIs

\[ \alpha^{95} = \text{at each time instant} \]
Extensive test for 5000 transients

59 Validation transients

>> Overall Coverage = 94.2%
Is the method able properly to represent all the uncertainty sources?

1. Uncertainty in signal measurements
2. Intrinsic stochasticity of the plant processes
3. Uncertainty in AAKR model parameters
4. Incompleteness of training data (Empirical Models)
Uncertainty in signal measurements
Uncertainty in signal measurements

- Signal #4 with 5 Noise Levels

- Overall Coverage (%)
  - Noise Level: 1, 2, 3, 4, 5
  - Coverage: 93%, 94%, 95%, 96%, 97%

- PI Width
  - Noise Level: 1, 2, 3, 4, 5
  - PI Width: 0.01, 0.02, 0.03, 0.04

GREAT JOB!
Intrinsic stochasticity of the plant processes

Data Simulation

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<th>μ ~</th>
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<td>1</td>
<td>U(0.475,0.525)</td>
<td>U(2.325, 2.575)</td>
<td>U(0.325,0.375)</td>
</tr>
<tr>
<td>2</td>
<td>U(0.45,0.55)</td>
<td>U(2.2, 2.7)</td>
<td>U(0.3,0.4)</td>
</tr>
<tr>
<td>3</td>
<td>U(0.425,0.575)</td>
<td>U(2.075, 2.825)</td>
<td>U(0.275,0.425)</td>
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<tr>
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<td>U(0.4,0.6)</td>
<td>U(1.95, 2.95)</td>
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Intrinsic stochasticity of the plant processes

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Overall Coverage (%) vs Parameter Range

PI Width (X4) vs Parameter Range
3 Uncertainty in AAKR model parameters

Bandwidth (h) Values

1.5
0.9
0.02
0.009
0.005

h1 h2 h3 h4 h5 h6 h7 h8
Treatment of Uncertainty Sources

Uncertainty in AAKR model parameters

Bandwidth (h) Values

- 1.5
- 0.9
- 0.02
- 0.009
- 0.005

Overall Coverage (%)

PI Width

h Values

Great Job!
Incompleteness of training data (Empirical Models)
Incompleteness of training data (Empirical Models)
Conclusions

CONTEXT

Condition Based Maintenance (CBM)

↓

Fault Detection System

↓

Reconstruction Model
**CONTEXT**

Condition Based Maintenance (CBM)

Fault Detection System

Reconstruction Model

**IN THIS WORK**

- Development of a method to associate a Prediction Interval to the model reconstructions:
  1. Scale Factor
  2. Order Statistics

- The method has been able to represent all the sources of uncertainties:
  1. Uncertainty in signal measurements
  2. Intrinsic stochasticity of the plant processes
  3. Uncertainty in AAKR model parameters
  4. Incompleteness of training data (Empirical Models)
Future Work

1. Validation of the proposed method using real data.
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2. When should we trigger the alarm?
1. Validation of the proposed method using real data.

2. When should we trigger the alarm?

3. Investigation of the Operator Attitude towards the Alarms provided by the Alarm System and the execution of CBM tasks.
Thank You
Questions?