MARIE CURIE ACTIONS

Energy-SmartOps

Integrated Control and Operation of Process, Rotating Machinery and Electrical Equipment

MULTIVARIATE STATISTICAL PROCESS MONITORING

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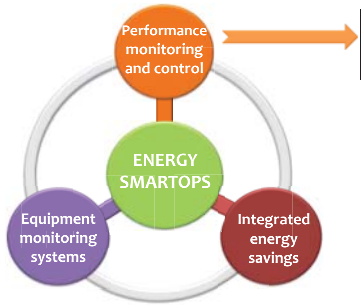
1. My Project in SmartOps

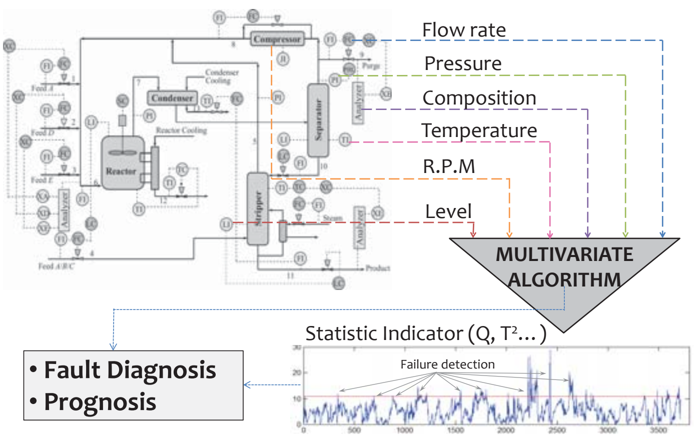


To devise new algorithms for overall performance monitoring and control.

WORK PACKAGE 3: MAINTENANCE AND DIAGNOSIS

ESR-D	ESR-H	ESR-I
Multivariate statistical process predictive monitoring using operational data.	Interconnections between process, mechanical and electrical equipment.	Reactive performance-based maintenance planning for process plants.

2. Problem Statement



3. Methodology: Canonical Variate Analysis

- **Data driven:** Not based on first principle equations.
- **Multivariate:** Takes into account correlation between variables.
- **Dimensionality reduction:** Selection of the most relevant information.
- **Fault detection:** A scalar statistic (Q, T²) can characterize multi-dimensional data variability.

✓**Dynamic:** Time correlation.

✓**State-space based:** More suitable for dynamic monitoring.

✓**System identification:** By linear regression using process data.

✓**Nonlinearities:** Estimation of actual probability density functions through kernel density estimations.

Mathematical Procedure:

$$[y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8, y_9, y_{10}, \dots y_n]$$

Time k

$$y_{p,k} = \begin{bmatrix} y_k \\ y_{k-1} \\ \vdots \\ y_{k-p+1} \end{bmatrix} \qquad y_{f,k} = \begin{bmatrix} y_{k+1} \\ y_{k+2} \\ \vdots \\ y_{k+f} \end{bmatrix}$$

Covariance Matrices:

$$\Sigma_{pp} = \frac{1}{M-1} Y_p Y_p^T \quad \Sigma_{ff} = \frac{1}{M-1} Y_f Y_f^T \quad \Sigma_{fp} = \frac{1}{M-1} Y_f Y_p^T$$

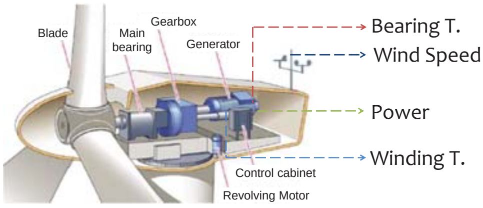
Hankel Matrix:

$$H = \Sigma_{ff}^{-1/2} \Sigma_{pf} \Sigma_{pp}^{-1/2} = UDV^T \begin{cases} UU^T = VV^T = I \\ D_{i,j} = 0 \; if \; (i \neq j) \end{cases}$$

Canonical variates and indicator:

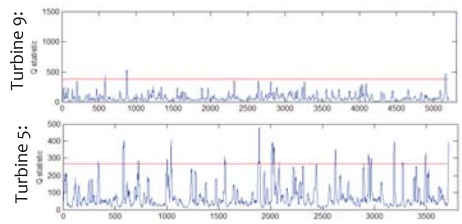
$$\underset{r \times m \cdot p}{J} = V_r^T \Sigma_{pp}^{-1/2} \qquad z = J \cdot Y_p \qquad T_j^2 = \sum_{i=1}^{i=r} z_{i,j}^2$$

4. CVA Application Example: Wind Turbine Data



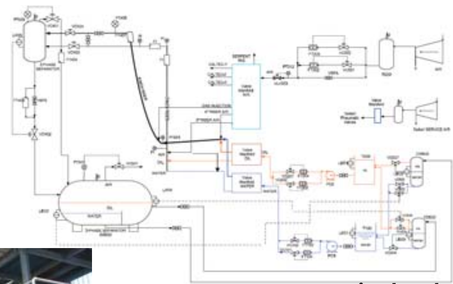
•Two different wind turbines: Wind Turbine 9 (healthy) and Wind Turbine 5 (faulty).

•Samples taken every 10 minutes September 2008-December of 2009.



5. Model Validation: Experimental Data

Experimental **data will be acquired** in the 3 phase test rig at Cranfield University. Real **faults will be introduced** in the system to obtain performance data under faulty conditions.



Test rig sketch

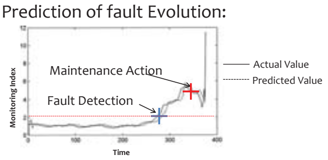
3 phase flow facility:

The results obtained in those experiments will be made available for other ESR's working in the field of condition monitoring, constituting the **Cranfield case study.**

6. Future Work

Theoretical Work:

Prediction of fault Evolution:



Linear state-space model: $\begin{cases} x_{t+1} = \Phi x_t + G u_t + w_t \\ y_t = H x_t + A u_t + B w_t + v_t \end{cases}$

$$m_t = J y_{p,t} \qquad \begin{bmatrix} m_{t+1} \\ y_t \end{bmatrix} = \begin{bmatrix} \Phi & G \\ H & A \end{bmatrix} \begin{bmatrix} m_t \\ u_t \end{bmatrix} + \begin{bmatrix} I & 0 \\ B & I \end{bmatrix} \begin{bmatrix} w_t \\ v_t \end{bmatrix}$$

$$\begin{pmatrix} \Phi & G \\ H & A \end{pmatrix} = \mathrm{cov}\left[\begin{pmatrix} m_{t+1} \\ y_t \end{pmatrix}, \begin{pmatrix} m_t \\ y_t \end{pmatrix} \right] \cdot \mathrm{cov}^{-1}\left[\begin{pmatrix} m_t \\ y_t \end{pmatrix}, \begin{pmatrix} m_t \\ y_t \end{pmatrix} \right]$$

Development and implementation of MVA for Condition Monitoring:

✓Develop Fault and Prognostic Algorithms (FAPA) based on informed literature.

✓Validation and optimization of the models using experimental data.

✓**Secondment in ABB-DE:**

- ✓ Refine models based on observations of on-site data.
- ✓ Develop software tool integrating models developed with maintenance protocols and strategies for industrial use.

Cranfield UNIVERSITY ABB energy smartOps

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