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An application of kernel spectral clustering to predictive maintenance

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BIL workshop, 15/07/2014, Leuven (Belgium)

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2. Spectral clustering (SC)
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A proper maintenance of industrial machines allows to:

- minimize downtime
- increase safety
- reduce costs.



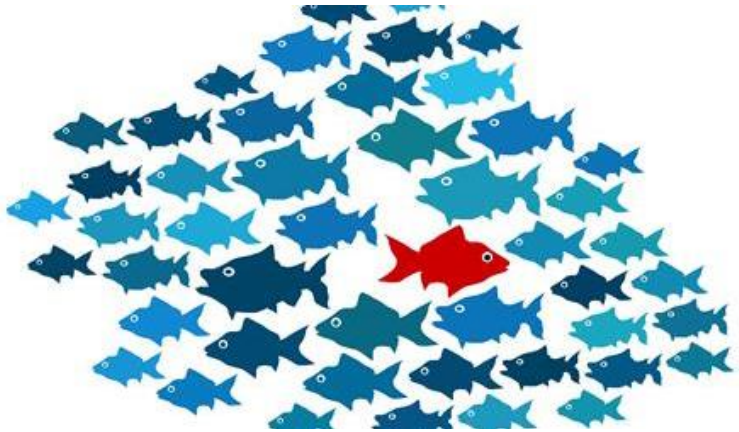
Three main types of maintenance exist*:

- corrective maintenance ➔ performed only when the machine fails
- preventive maintenance ➔ based on periodic replacement of components
- predictive maintenance ➔ planned according to sensor data.

* *Venkatasubramanian, V., Rengaswamy, R., Kavuri, S., 2003. A review of process fault detection and diagnosis. Computers and chemical engineering 27 (3), 293–346.*

Predictive maintenance can be performed in two ways:

- manually ➔ an operator chooses when to replace components
  - ✖ subjective decision!
  - ✖ can be disadvantageous in terms of costs.
- automatically ➔ a data-driven model suggests an optimal scheduling
  - ✔ less prone to human errors
  - ✔ more cost effective.



Novelty detection methods can detect machine's degradation from sensor reading.

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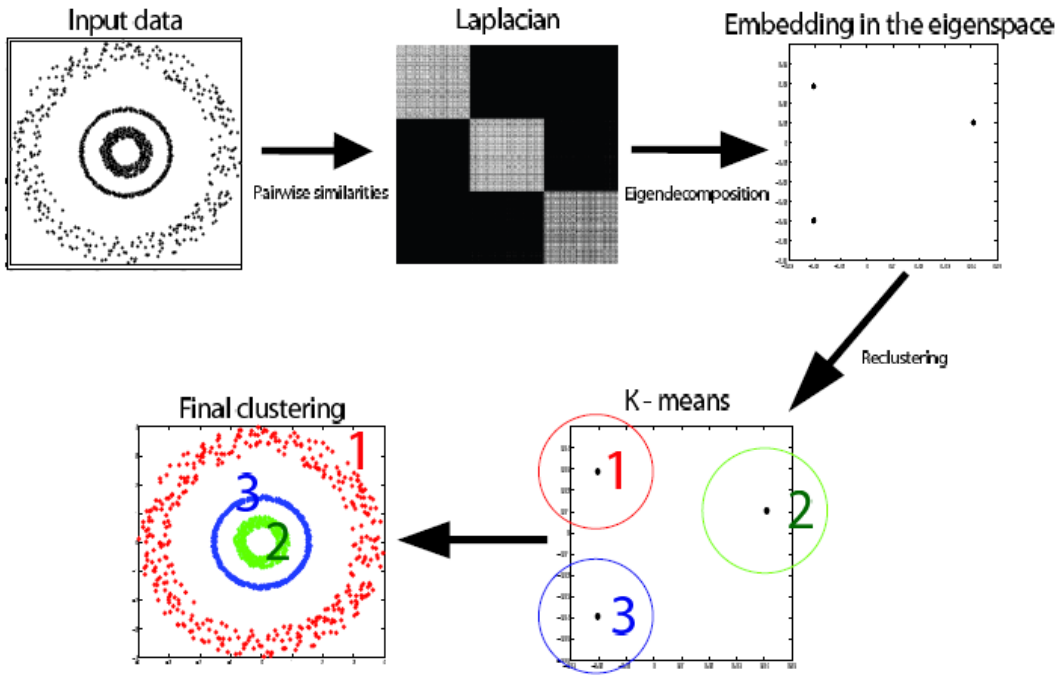
2 – The classical algorithm

SC discovers the structure of the data thanks to their mapping in the eigenspace of the Laplacian*:

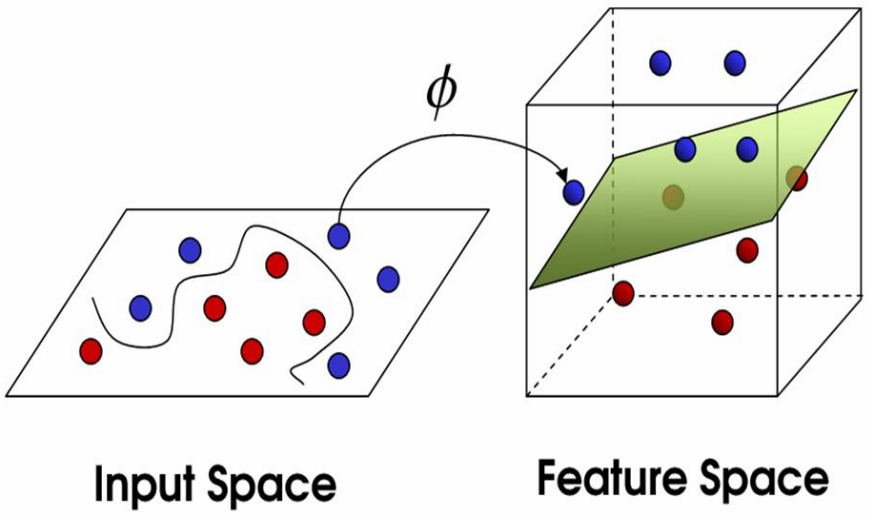


Main steps of the SC algorithm.

- ✔ can detect complex clustering boundaries
- ✔ deterministic (does not depend on initial conditions like e. g. k-means)
- ✖ the number of clusters should be provided beforehand
- ✖ does not allow out-of-sample extension.

* *von Luxburg, U., 2007. A tutorial on spectral clustering. Statistics and Computing 17 (4), 395–416.*

SVMs are a learning algorithm represented in terms of a convex problem and a primal-dual framework:



Nonlinear relations in data are discovered through the use of nonlinear embedding mappings.

In this work we have used a particular class of SVMs called Least Squares SVMs*:

- Quadratic Loss
- Equality constraints.

* *Suykens et al., Least Squares Support Vector Machines, World Scientific Publishing Company (2002).*

The KSC model represents a spectral clustering formulation in a learning framework*:

Primal:

$$\min_{w^{(l)},e^{(l)},b_l} \quad \frac{1}{2}\sum_{l=1}^{k-1} w^{(l)^T} w^{(l)} - \frac{1}{2N_{\mathrm{Tr}}}\sum_{l=1}^{k-1} \gamma_l e^{(l)^T} D^{-1} e^{(l)} \tag{1}$$

$$\text{subject to} \quad e^{(l)} = \Phi w^{(l)} + b_l 1_{N_{\mathrm{Tr}}}.$$

Dual:

$$D^{-1} M_D \Omega \alpha^{(l)} = \lambda_l \alpha^{(l)}. \tag{2}$$

Generalization:

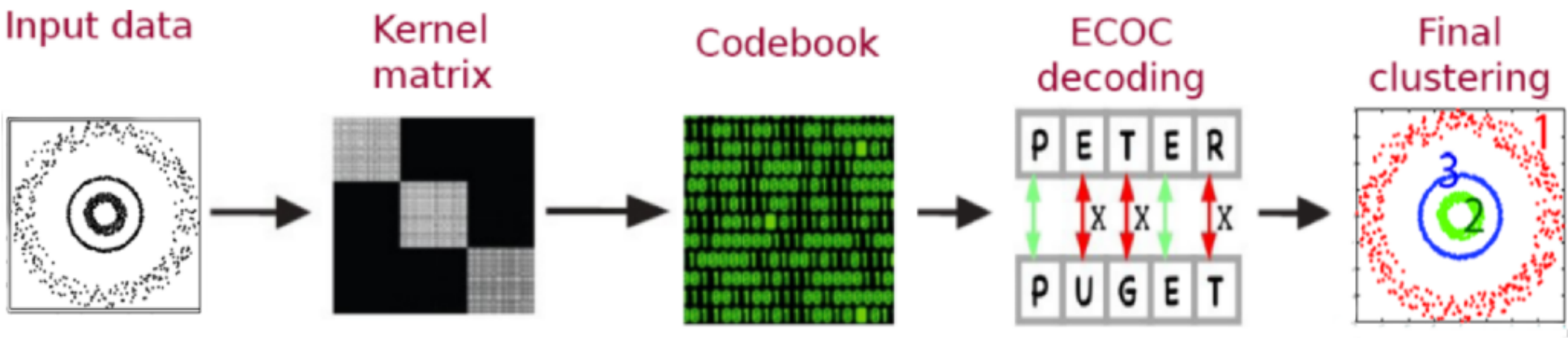
$$e^{(l)}_{\mathrm{test}} = \Omega_{\mathrm{test}} \alpha^{(l)} + b_l 1_{\mathrm{N}}. \tag{3}$$

Notation:

- $\varphi : \mathbb{R}^d \to \mathbb{R}^{d_h}$ indicates the mapping of the data points $\{x_i\}_{i=1}^{N_{\mathrm{Tr}}}$ to the feature space
- $\gamma_l \in \mathbb{R}^+$ are regularization constants
- Φ is the $N \times d_h$ feature matrix $\Phi = [\varphi(x_1)^T; \ldots; \varphi(x_{N_{\mathrm{Tr}}})^T]$
- Ω denotes the $N_{\mathrm{Tr}} \times d_h$ kernel matrix with ij-th entry $\Omega_{ij} = K(x_i, x_j) = \varphi(x_i)^T \varphi(x_j)$
- D means the degree matrix related to the kernel matrix Ω.

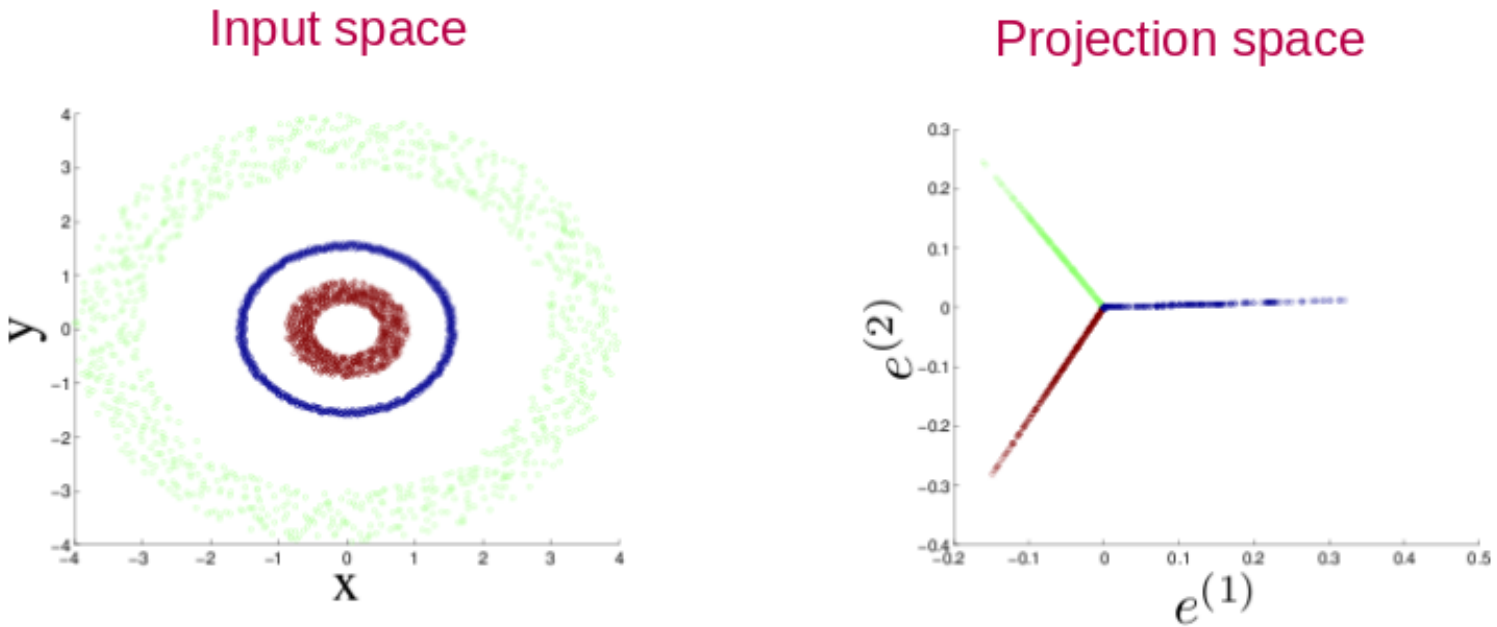
* *Alzate and Suykens, TPAMI 32 (2), 2010, pp. 35-47.*

Main steps present in the KSC algorithm:



Once a model has been trained offline, it can be used online thanks to eq. (3).

- **Issue**: the correct tuning of model's (hyper-) parameters is crucial
- **Solution**: in KSC, we can exploit the structure of the $e^{(l)}$ to perform model selection ➔ balanced linefit (BLF) criterion.



The BLF criterion achieves a high value when clusters look like lines in the $e^{(l)}$ space.

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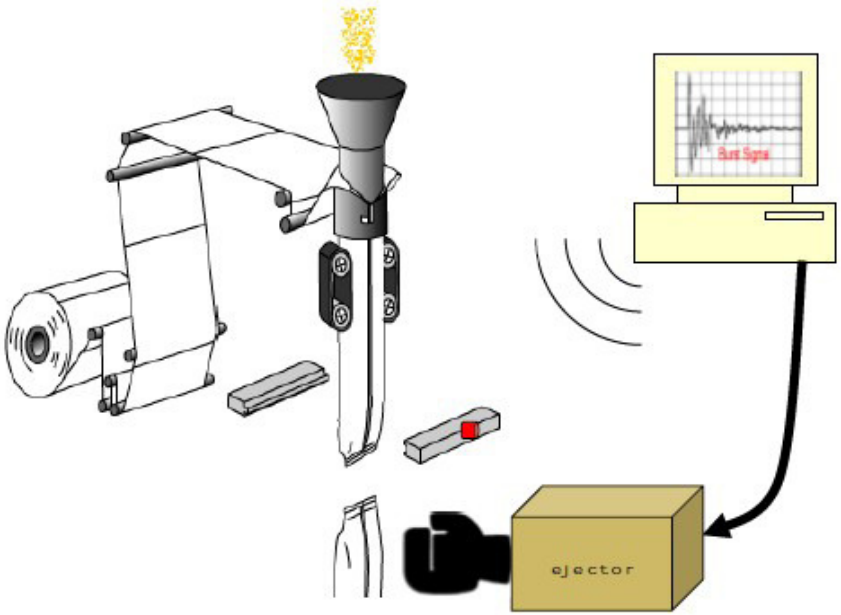
3 – The experimental design*

- A vertical form fill and seal (VFFS) machine is equipped with accelerometers
- The machine is deteriorated on purpose
- The accelerometers monitor the dirt accumulation in the sealing jaws
- An operator performs maintenance actions.



Seal quality monitoring in a packing machine.

* *Experiment executed within the framework of the project "Prognostic for Optimal Maintenance (POM)".*

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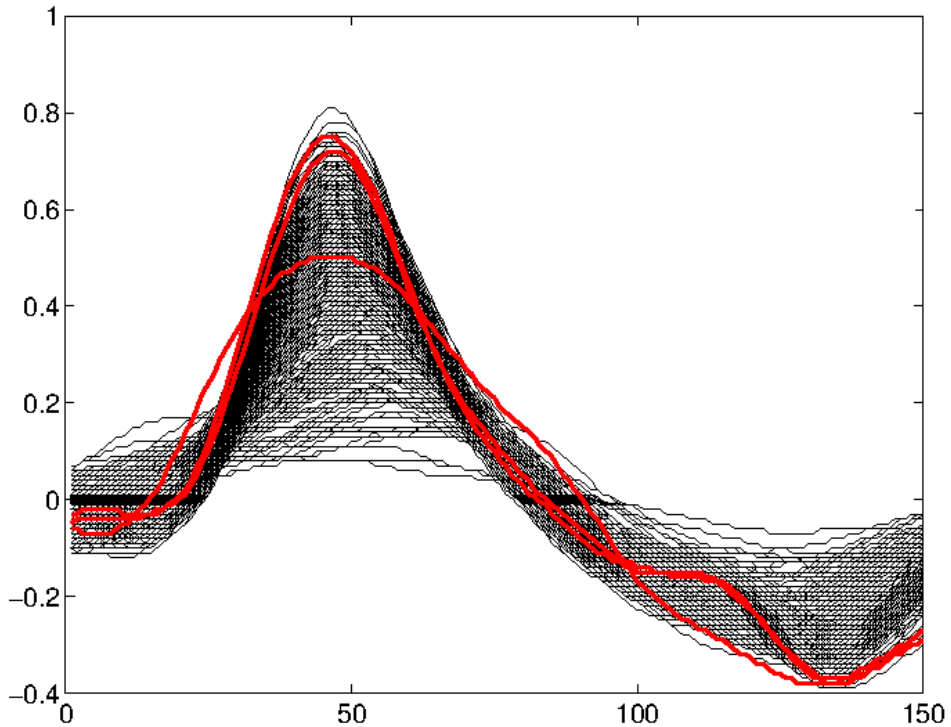
The data consist of the vibration signals collected by the accelerometers:

- 771 time-series of dimension 150
- each times-series is associated with a given processed bag
- 3 external maintenance actions are performed.



Vibration signals from accelerometers. Signals at maintenance are depicted in red.

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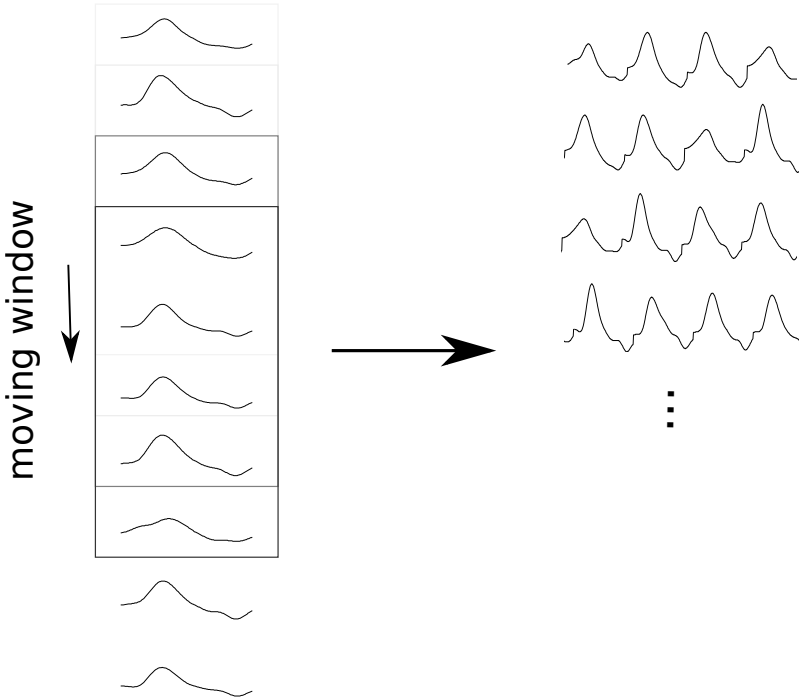
Issue: to model the degradation process leading to maintenance we need to incorporate historical information into KSC.
Solution: concatenation of vibration signals.

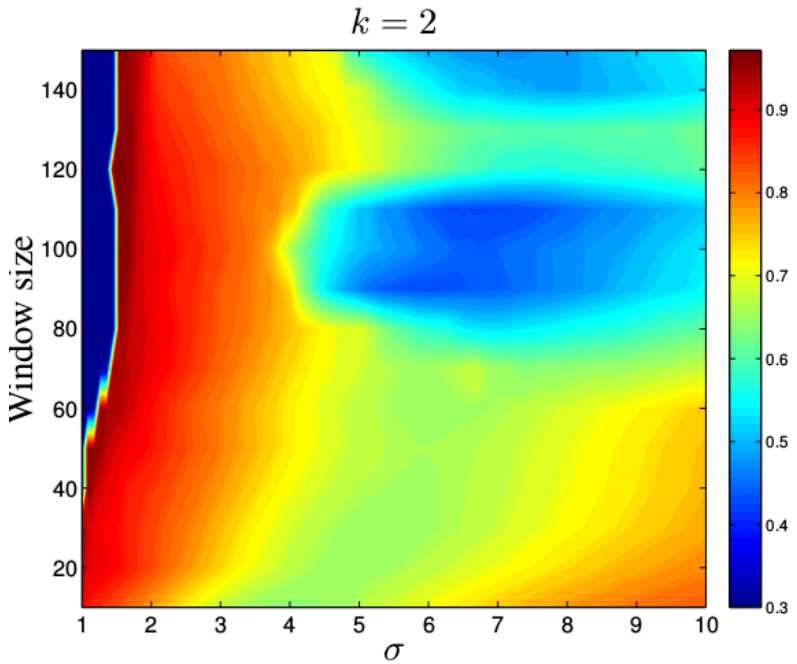


Pre-processing procedure when using KSC for predictive maintenance.

Questions:

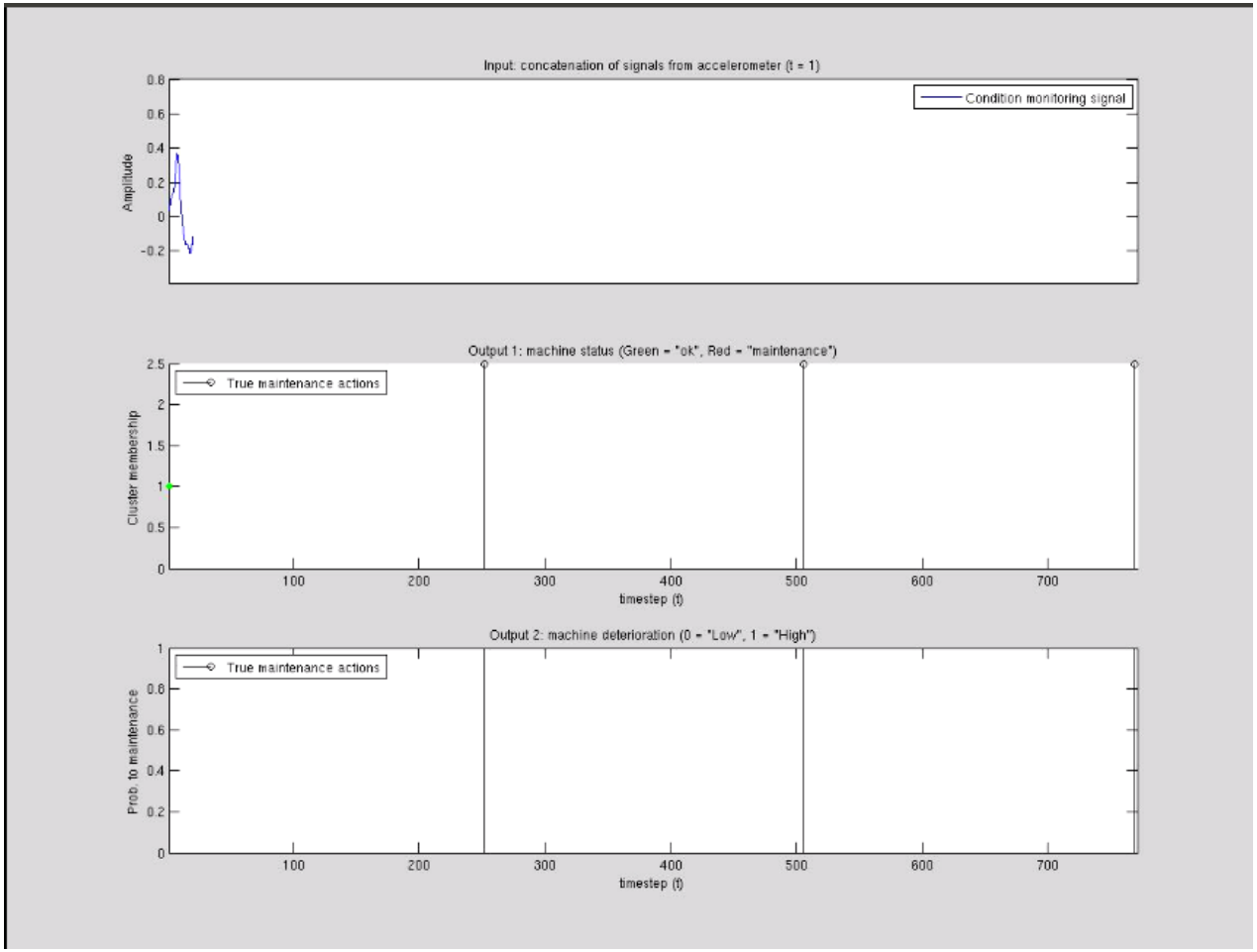
- how many signals do we have to concatenate?
- how many clusters are present?
- what is the optimal bandwidth σ of the RBF kernel?

Answer: BLF-based model selection.



Window size = 40, $\sigma = 1.17$, *number of clusters* $= 2$.

4 – Results*



Online fault detection via KSC.

** Langone R., Alzate C., De Ketelaere B., Suykens J.A.K, "Kernel spectral clustering for predicting maintenance of industrial machines", in Proc. of the Symposium Series On Computational Intelligence (SSCI 2013), Singapore, Apr. 2013, pp. 39-45.*

- *Venkatasubramanian, V., Rengaswamy, R., Kavuri, S., 2003. A review of process fault detection and diagnosis. Computers and chemical engineering 27 (3), 293–346.*
- *von Luxburg, U., 2007. A tutorial on spectral clustering. Statistics and Computing 17 (4), 395–416.*
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- *Alzate and Suykens, TPAMI 32 (2), 2010, pp. 35-47.*
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5 – Conclusions

- we applied kernel spectral clustering (KSC) to predict when a VFFS machine starts deteriorating
- KSC manages to detect in advance when the machine needs maintenance
- future work may be related to exploring the usage of semi-supervised techniques.



5 – Questions?

