Profile Monitoring, Process Monitoring & Multichannel Data Analysis in Manufacturing Applications

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Context of the study

In many situations the quality of a process is characterized by a relationship between two or more variables – a curve or a profile –

**Example of application in product-based SPC framework**: monitoring of roundness/cylindricity errors (analysis of technological signatures)


**Goal**: monitoring the stability over time of the observed patterns with respect to a reference one
A Real Test Case: High Pressure Waterjet Cutting

High pressure WJ cutting is an unconventional machining process that is being used in nearly every manufacturing sector today.

The pressure signal is characterized by a repeating pattern in time, consisting of dynamic pressure oscillations around the static level.

Such a signal can be used to detect faults affecting the most critical components of the machine tool.
A Fourier basis was chosen to smooth the profiles and to estimate a model able to characterize normal health conditions. The first six harmonics are included into the model.

A Time Warping approach was used for curve registration. Warping functions are third degree polynomial functions.
Results

Monitored vector:

$$\beta_j = (c_{1,j}, c_{2,j}, \ldots, c_{2K,j}, a_{1,j}, a_{2,j}, \ldots, a_{N,j}), \ j = 1,2,\ldots,n,$$

K=12 Fourier parameters \ N=3 warping parameters

Datasets

Parameter vector monitoring

- Training: n=130
- Testing: n=500
- \(p=K+N=15\) variables

Direct signal monitoring (e.g. PCA)

- Training: n=130
- Testing: n=500
- \(p=8000\) datapoints
Profile monitoring performances are compared with a more conservative method applied in industry, which consists of computing synthetic indexes and applying a multivariate control chart on them (index-based approach).

<table>
<thead>
<tr>
<th>Monitoring Approach</th>
<th>Faulty Detection Percentage (%)</th>
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<tbody>
<tr>
<td></td>
<td>Fault a</td>
</tr>
<tr>
<td>Index-based</td>
<td>50.00</td>
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<tr>
<td>Profile Monitoring</td>
<td></td>
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<tr>
<td>I) Un-registered curves</td>
<td>100</td>
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<tr>
<td>II) Registered curves (only Fourier coeff.s monitored)</td>
<td>100</td>
</tr>
<tr>
<td>III) Registered curves (both Fourier &amp; warping coeff.s monitored)</td>
<td>100</td>
</tr>
</tbody>
</table>

Effects of two faults on the warping coefficients
Other applications (a few examples)

**In-process applications** (sensor signals)
- Process anomaly detection
- Tool breakage detection

**Post-process applications** (workpiece measures)
- Roundness error in turning
- Surface monitoring
- Vertical density profile of wood boards
Other Methods (single channel)

Different methods have been studied in a number of applications to model profile patterns and to extract relevant features. E.g.:

1. Functional Principal Component Analysis
2. Regression Spline Smoothing
3. Wavelet Analysis
4. Empirical Mode Decomposition
5. Etc…
Multi-way PCA

*Vectorized PCA* represents the most common extension of PCA to higher dimensions.

Other multi-way extensions of traditional PCA – *currently under study and development*.
Open Issues and Research Topics

Different issues implies the need for continuous improvement and research efforts:

1. Monitoring of multivariate correlated profile data (both within-profile and between profile correlation) – stationary and non-stationary time series

2. Efficient monitoring of large multivariate time series (high number of variables) – computational constraints imposed by real-time implementation

3. Monitoring of large multivariate datasets (high number of variables) without any assumptions about the data distribution

4. Monitoring of multi-channel data (multi-sensor data fusion): how to properly integrate information coming from different sources

5. Fast reaction to malfunctions (training dataset characterized by large p – number of variables – and small n – number of samples - )


