Machine learning and data analysis at the ZeMA condition monitoring testbed

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Digital technologies in industrial measurements

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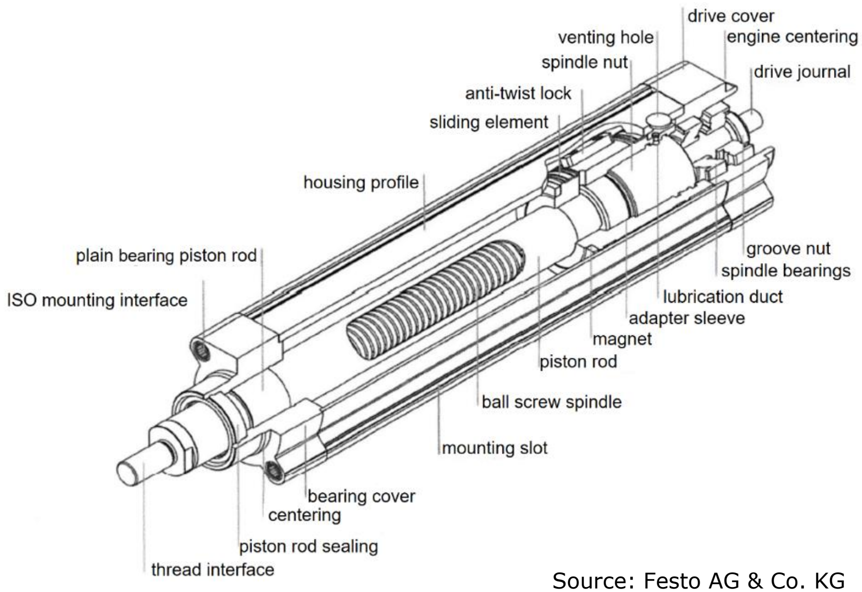
ZeMA testbed for electromechanical cylinders

- Testbed for condition monitoring, lifetime prognoses and end-of-line tests of electro-mechanical cylinders (EMCs) with a spindle drive
- Long-time high load and speed driving tests until a position error of the EMC occurs
- Relevant sensors and characteristic signal patterns can be identified for condition monitoring and remaining useful lifetime (RUL) estimation of the EMC
- Simplified installation
  - Tested EMC
  - Pneumatic cylinder (simulates the load on the EMC in axial direction)

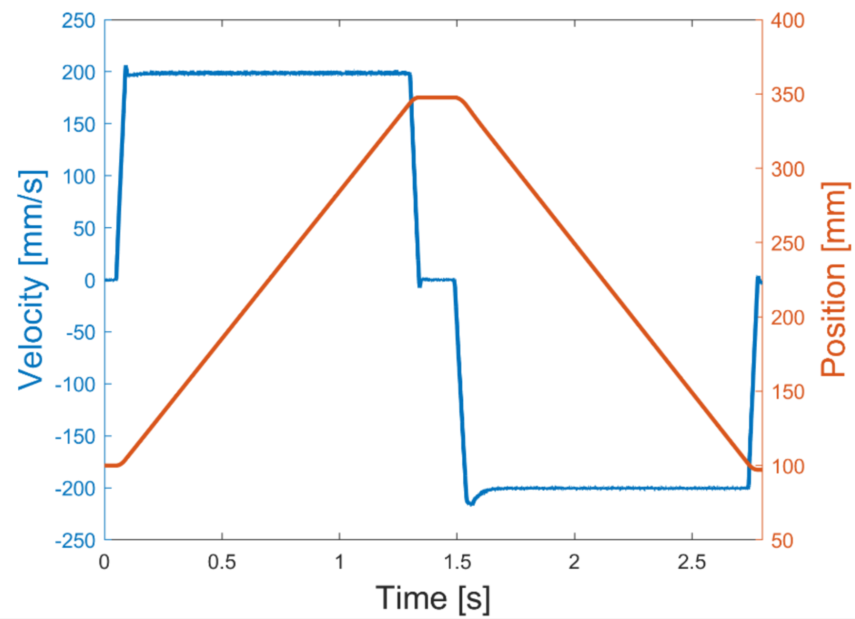


Source: Festo AG & Co. KG

High-quality measurement system at ZeMA testbed

- Working cycle consists of forward stroke, waiting time and return stroke
- Sensor technology (sampling rate) [1]
  - Three motor current sensors (each 1 MHz)
  - Three acceleration sensors (each 100 kHz)
    - at the ball bearing
    - at the plain bearing
    - at the piston rod
  - One ultrasonic microphone (100 kHz)
  - Four process sensors (each 10 kHz)
    - Axial force
    - Velocity
    - Pneumatic pressure
    - Active current

Velocity	200 [mm/s]
Axial force	7 [kN] (const. pulling)
Acceleration / Deceleration	5 [m/s²]
Stroke range	100 to 350 [mm]
Waiting time	150 [ms]
Cycle length	2.8 [s]



[1] T. Schneider, N. Helwig, S. Klein, and A. Schütze, "Influence of Sensor Network Sampling Rate on Multivariate Statistical Condition Monitoring of Industrial Machines and Processes," *Proceedings*, vol. 2, no. 13, p. 781, Dec. 2018; doi: 10.3390/proceedings2130781

PTB measurement system: SmartUp Unit (SUU)

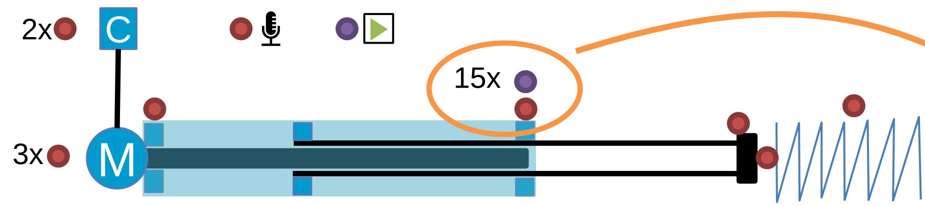
MS5837	
Temperature	1 Hz
Air Pressure	1 Hz

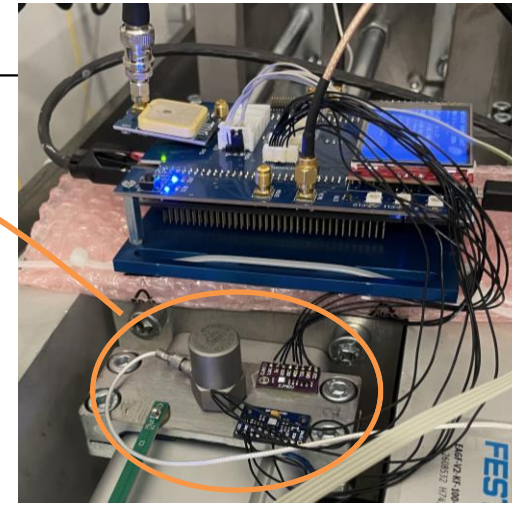
MPU9250	
X Acceleration	1000 Hz
Y Acceleration	1000 Hz
Z Acceleration	1000 Hz
X Angular speed	1000 Hz
Y Angular speed	1000 Hz
Z Angular speed	1000 Hz
X Magnetic flux density	100 Hz
Y Magnetic flux density	100 Hz
Z Magnetic flux density	100 Hz
Temperature	1000 Hz

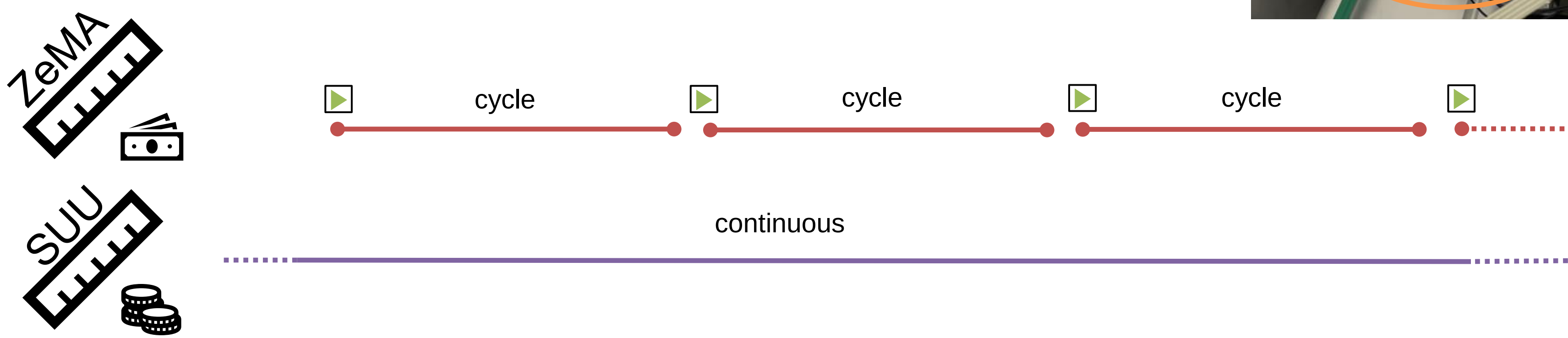
BMA280	
X Acceleration	2000 Hz
Y Acceleration	2000 Hz
Z Acceleration	2000 Hz

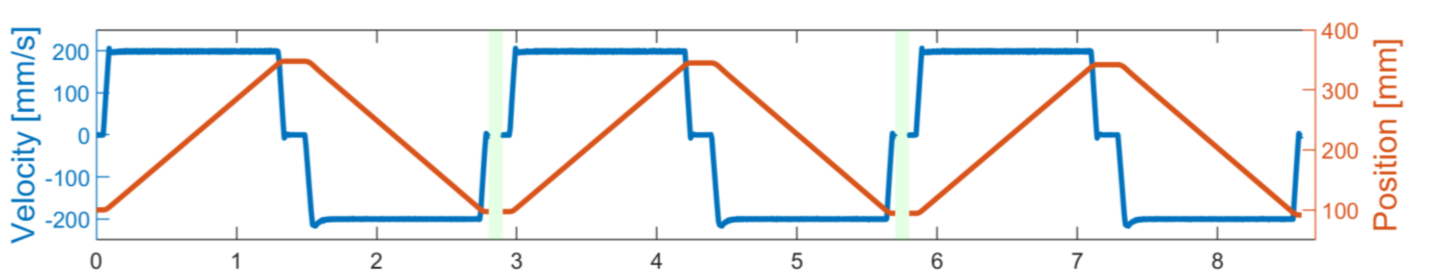
Kistler 8712A5M1 (ZeMA)	
Z Acceleration	100 kHz

Extension of the ZeMA testbed



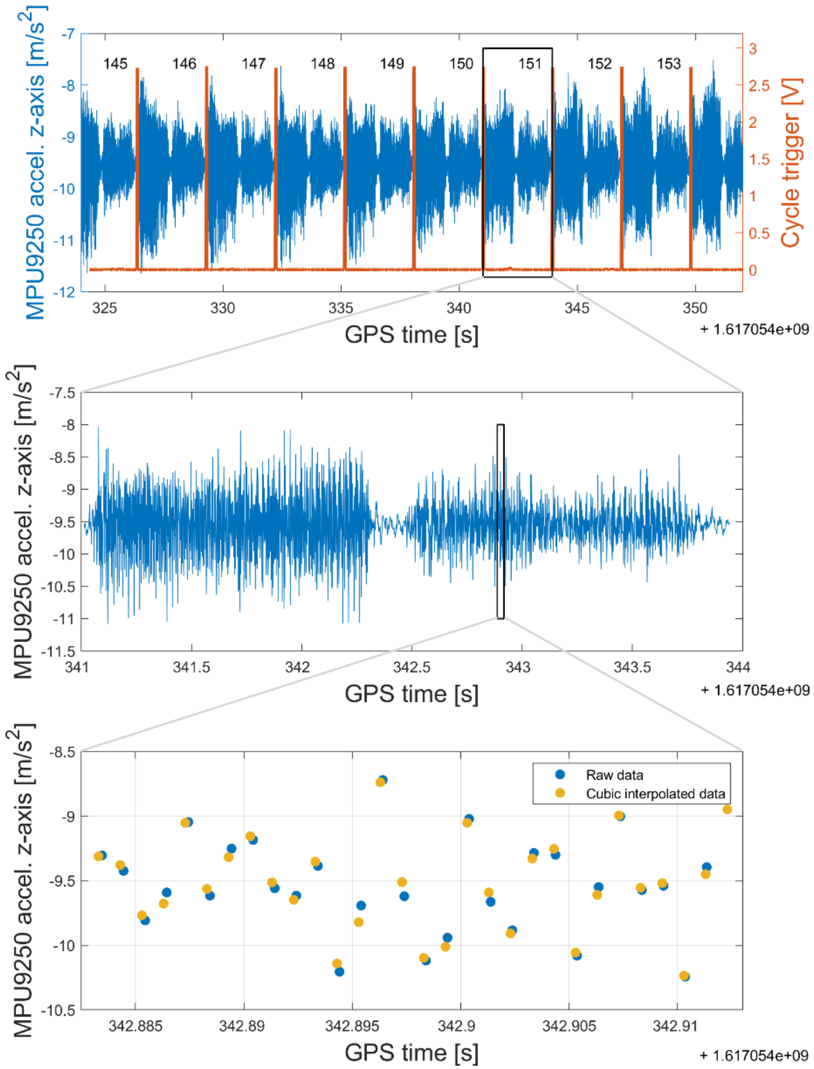




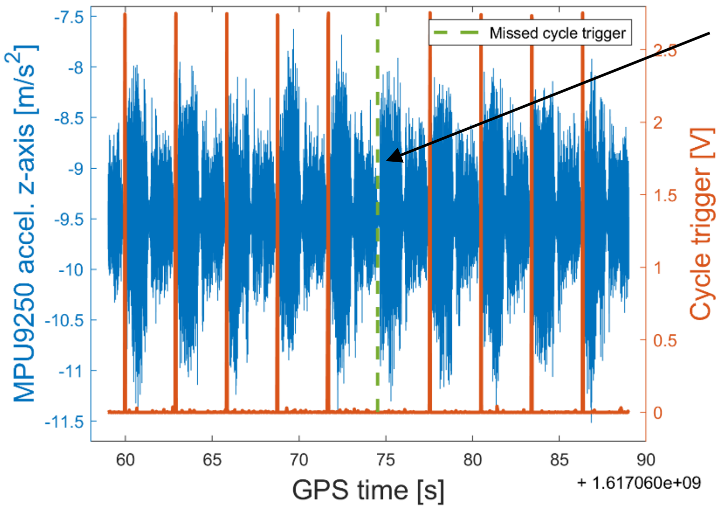


Preprocessing of the SUU data

- Starting point: lifetime measurement of approx. 370h with continuous time series signal in which individual cycles need to be detected
- Linking between both measurement systems: trigger signal of the ZeMA testbed indicates beginning of a cycle
- Timestamped SUU raw data must be interpolated as oscillator of the low-cost system is not on point
- Preprocessing seems to be a straightforward process

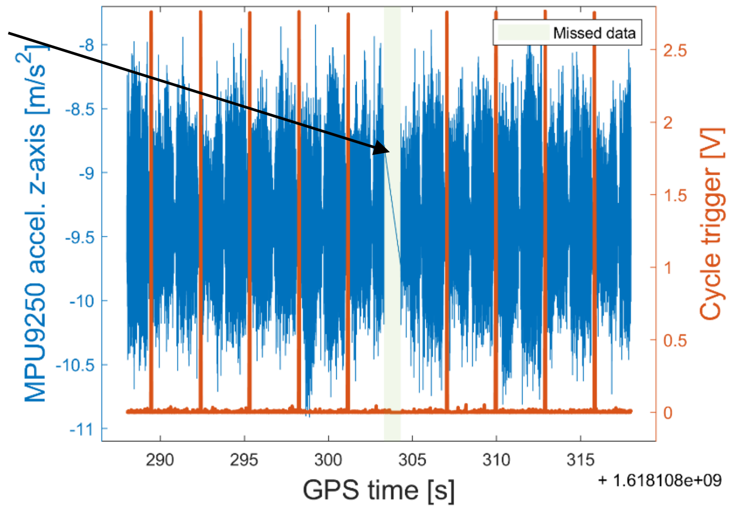


Problems during preprocessing

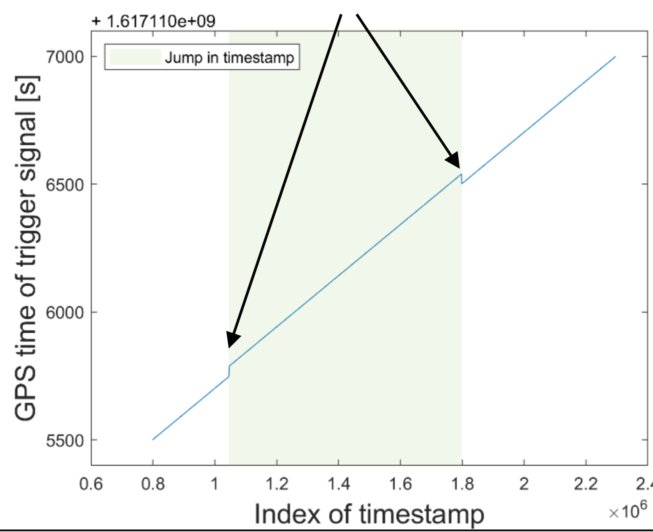


no trigger

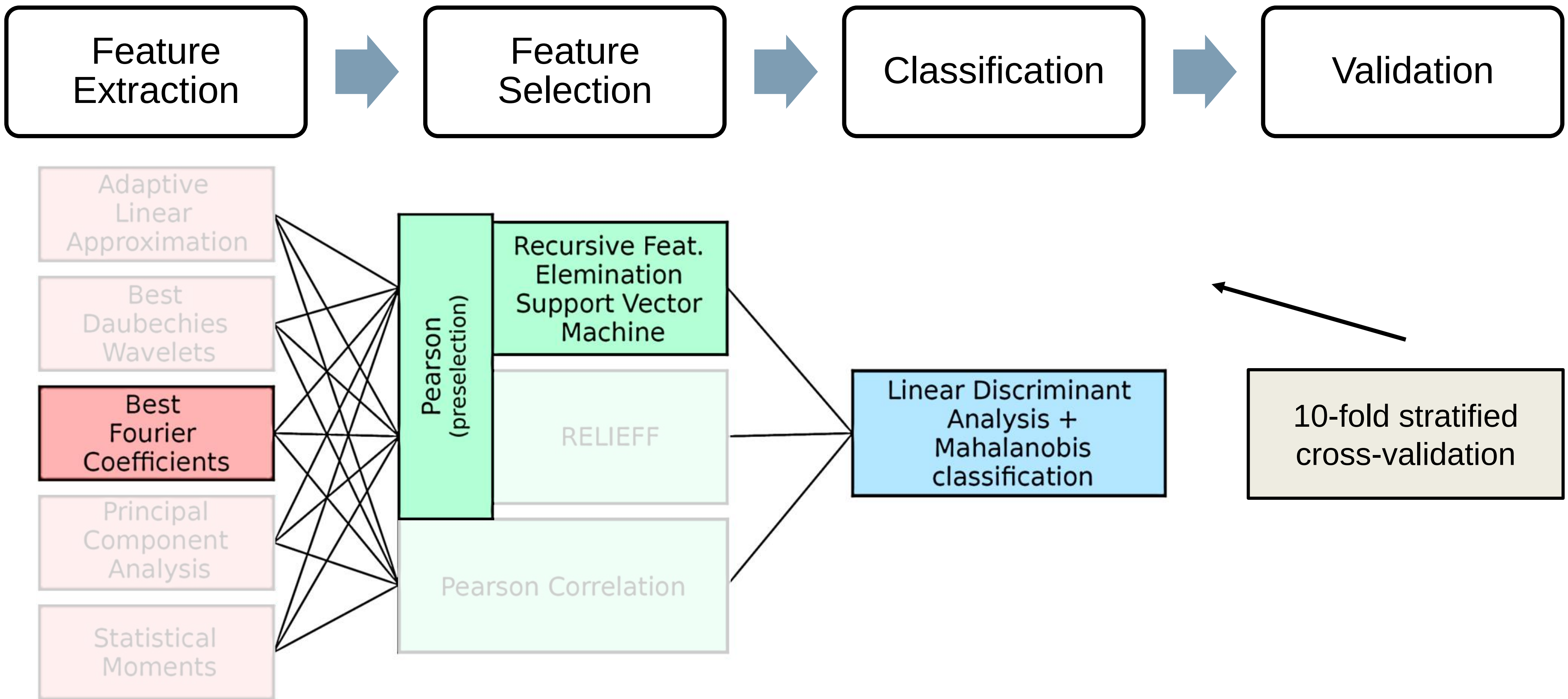
no data



40s timejumps

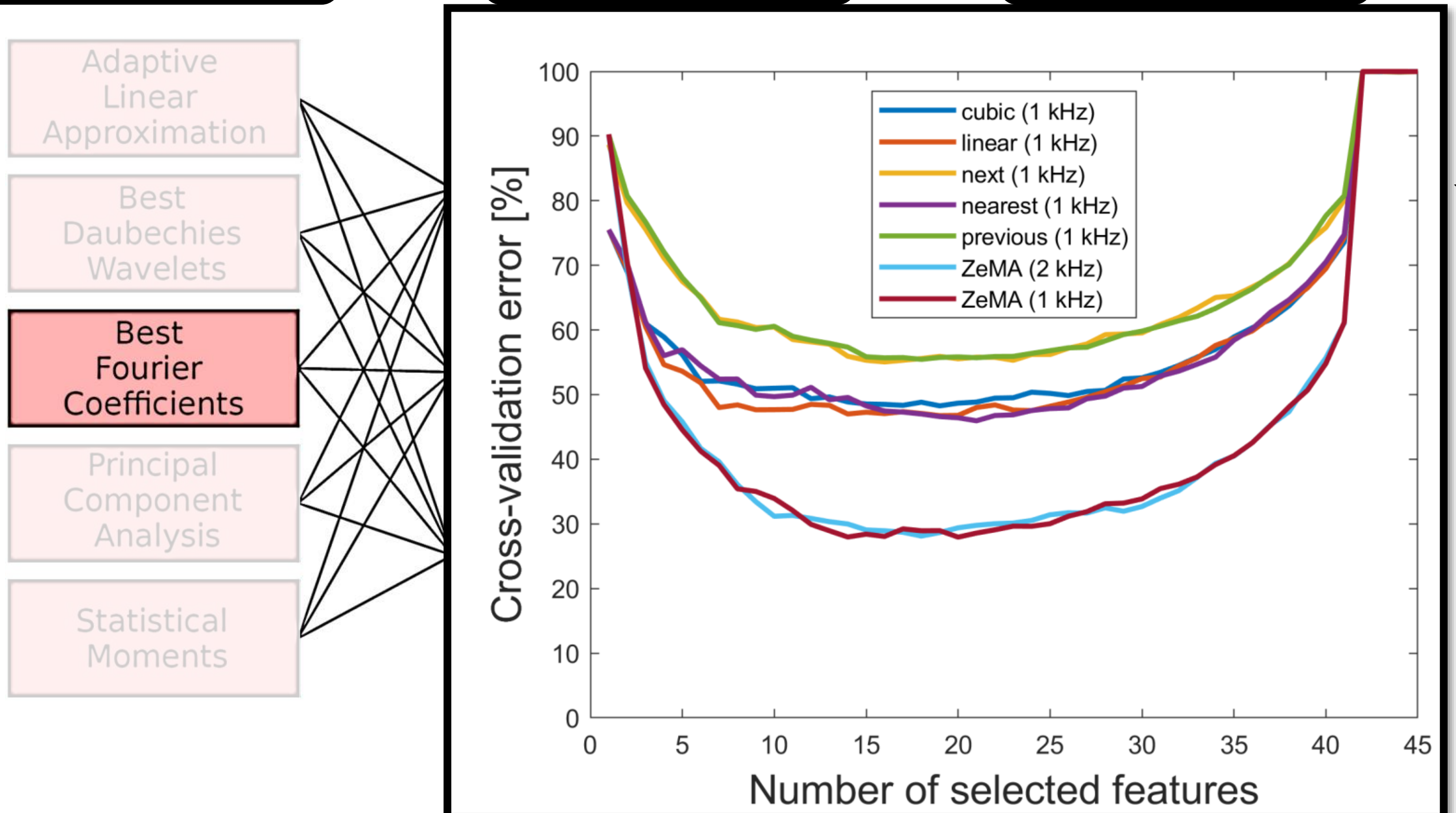


Automated Machine Learning Toolbox – Training



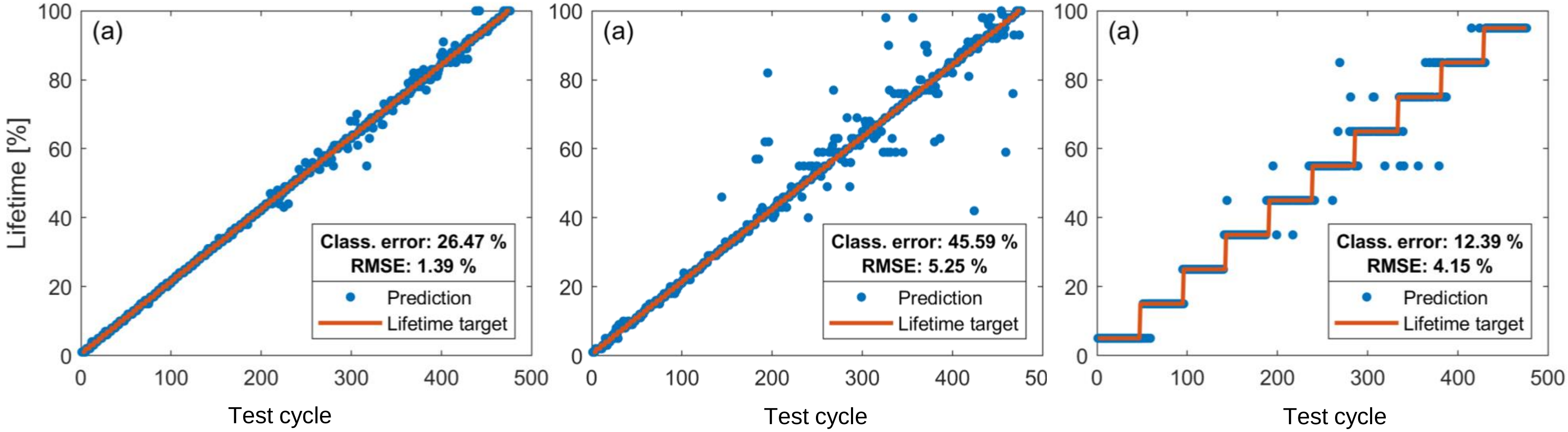
Automated Machine Learning Toolbox – Training

Feature Extraction → Feature Selection → Classification → Validation



10-fold stratified cross-validation

Lifetime Estimation (Results for 1kHz)



High-end,
1% target steps

Low-end, cubic,
1% target steps

Low-end, cubic,
10% target steps

Motivation – Why use uncertainty propagation in the ML toolbox?

- Basic metrological principles: Measurement uncertainties, calibration and thus traceability to the International System of Units (SI)

- If decisions are based on measurements, it is important to have high quality information of the results

- Measurement uncertainty of the used sensors

  → Express reliability of the ML results of the toolbox

- Automated ML toolbox does not take measurement uncertainty into account

GUM – an introduction

- *Guide to the Expression of Uncertainty in Measurement* (GUM), first published 1995
- Basis for the international comparison of measurement results
- Measurement result only complete with indication of measurement uncertainty
- Provides information for the calculation of measurement uncertainty
- Most common equation for uncertainty propagation are based on the ***L**aw of **P**ropagation of **U**ncertainty* (LPU)

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)}$$

- Partial derivatives: „sensitivity coefficients“

Extension of the automated ML toolbox

Feature extraction

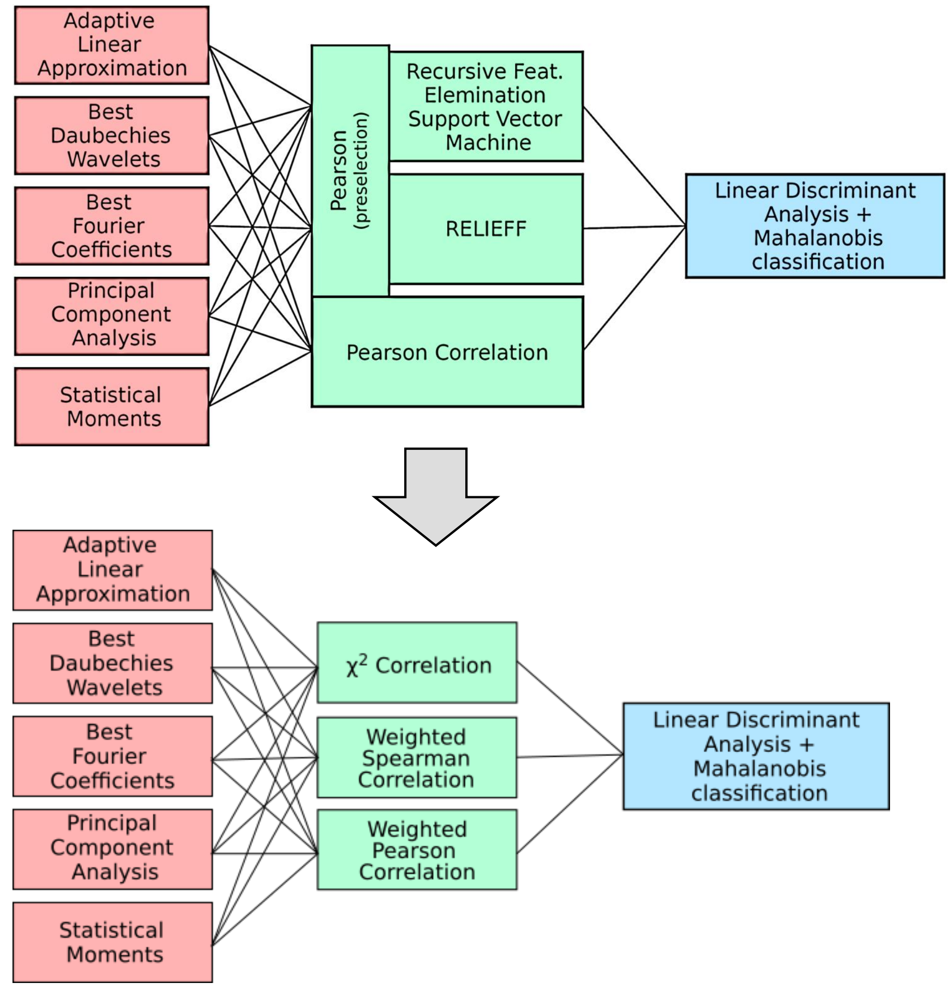
- ALA[2], BDW[3], BFC[4] and SM[3]: uncertainty calculation according to GUM (Guide to the Expression of Uncertainty in Measurement)
- PCA[2]: uncertainty calculation according to GUMS1 (GUM – Supplement 1)

Feature selection

- replace RFESVM and ReliefF by weighted Pearson, weighted Spearman, and χ^2 correlation

Classification

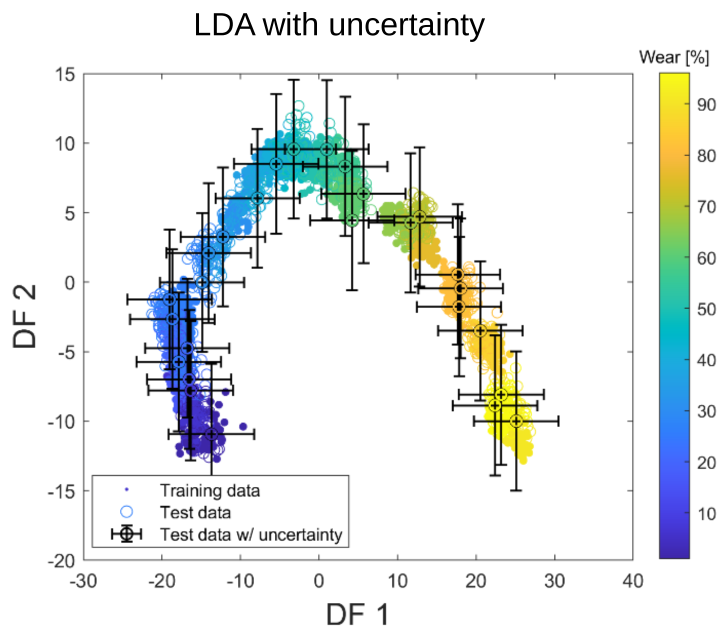
- LDA[4]: uncertainty calculation according to GUMS2 (GUM – Supplement 2)



[2] Dorst, T., Eichstädt, S., Schneider, T., and Schütze, A.: Propagation of uncertainty for an Adaptive Linear Approximation algorithm, SMSI 2020, pp. 366–367, https://doi.org/10.5162/SMSI2020/E2.3, 2020.
[3] will be published soon
[4] Eichstädt, S. and Wilkens, V.: GUM2DFT—a software tool for uncertainty evaluation of transient signals in the frequency domain, Measurement Science and Technology, 27, https://doi.org/10.1088/0957-0233/27/5/055001, 2016.

Summary and outlook

- ZeMA testbed for electromechanical cylinders and its extension with the SmartUp Unit
- Preprocessing revealed data problems → Never blindly trust new data, always include plausibility heuristics
- Automated ML toolbox with uncertainty propagation according to the GUM for uncertain measurement values



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Thank you for your attention!

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