Probabilistic long-term health index modeling, segmentation, and prediction in the presence of non-Gaussian noise

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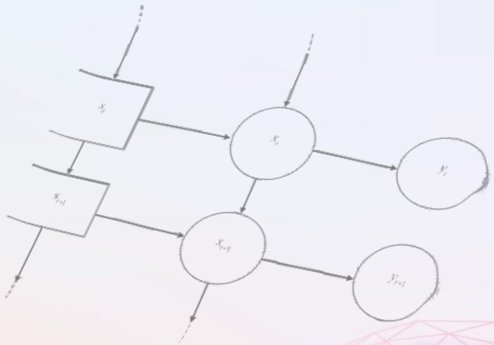
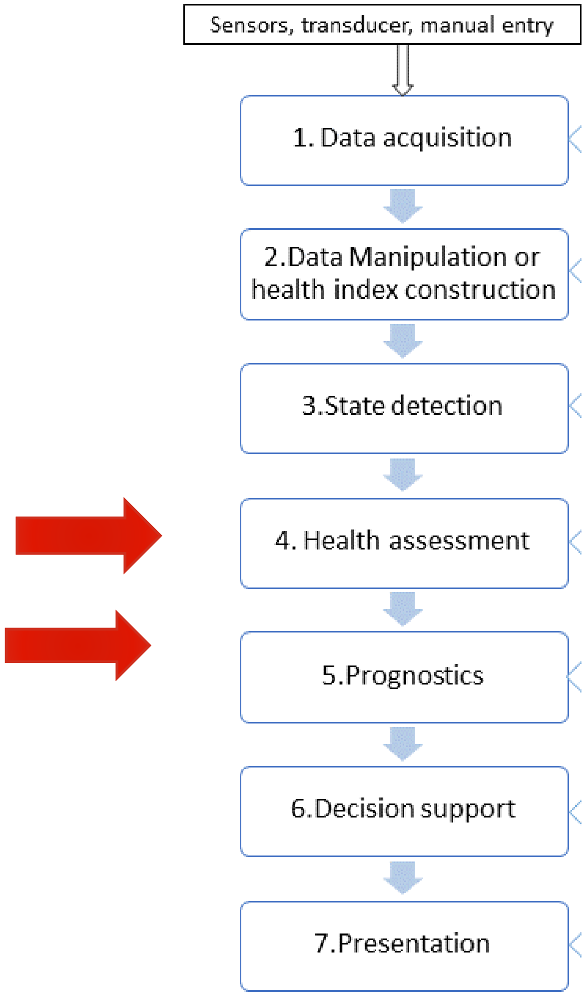


Outline

- Introduction
- Problem formulation
- Methodology
- Results
- Conclusion

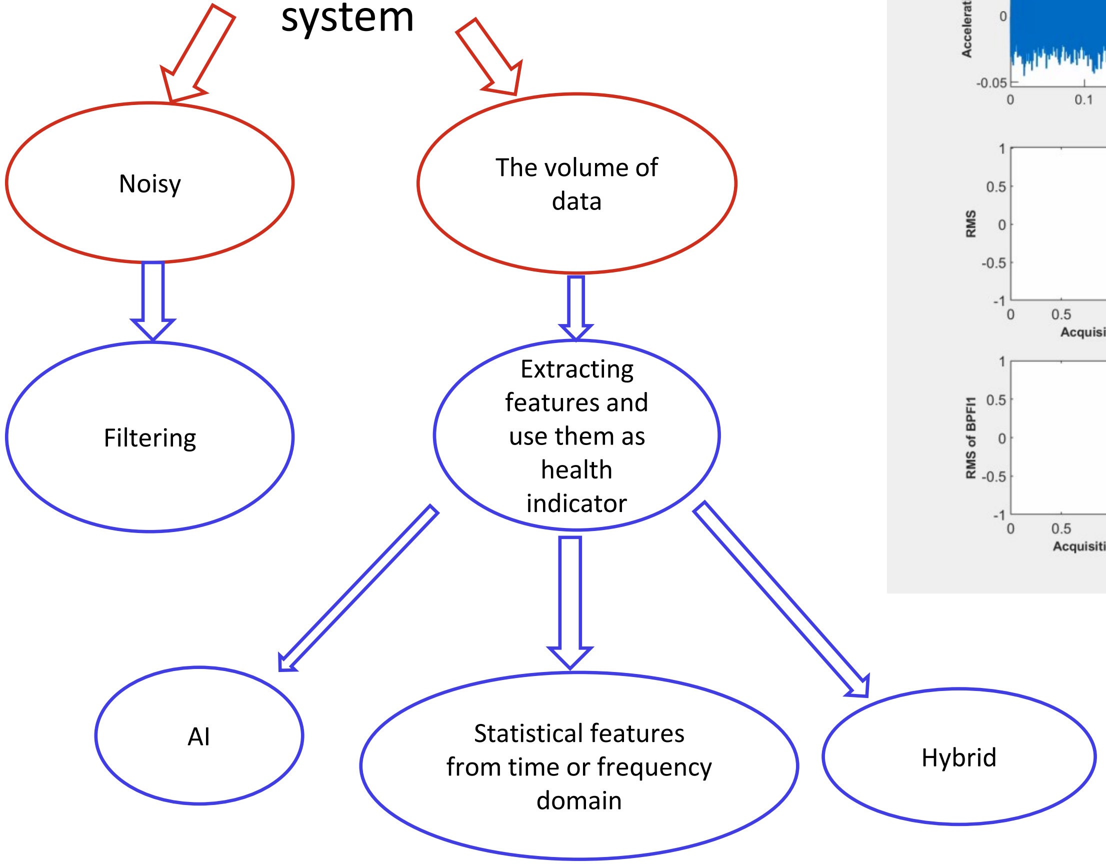
Condition based maintenance (CBM)

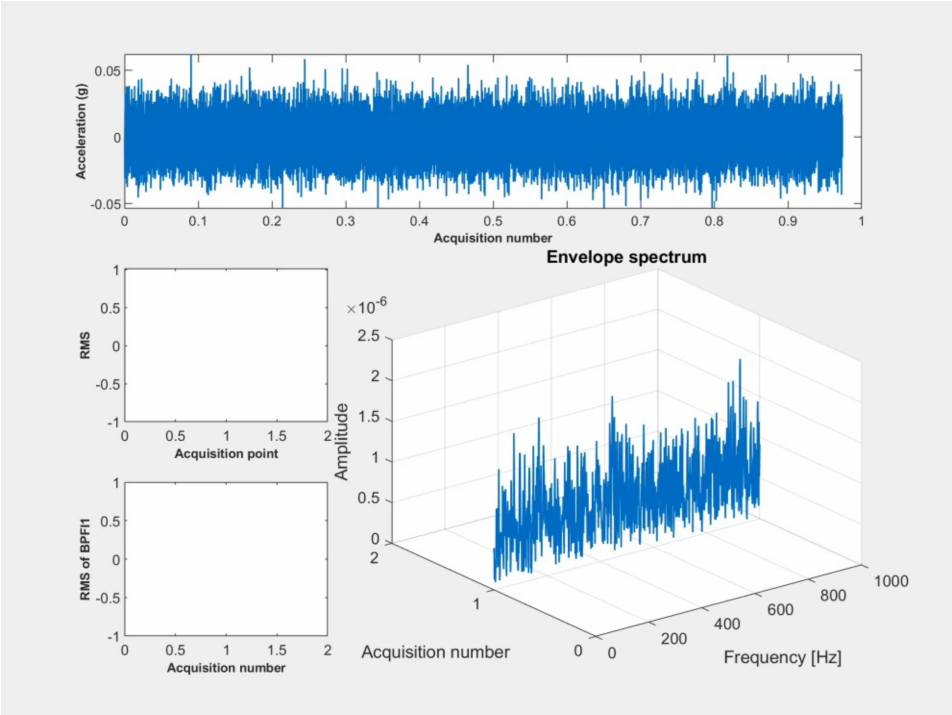
1. Data acquisition
2. Data manipulation and health index construction
3. State detection
4. Health assessment
5. Prognostics
6. Decision Support
7. Presentation

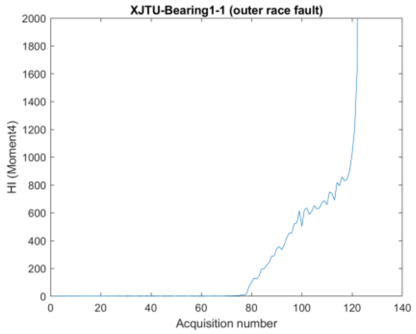


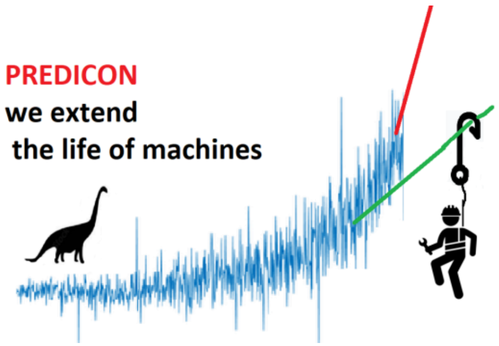
Data acquisition and data manipulation or health index construction

Raw data is acquired to monitor the state of system





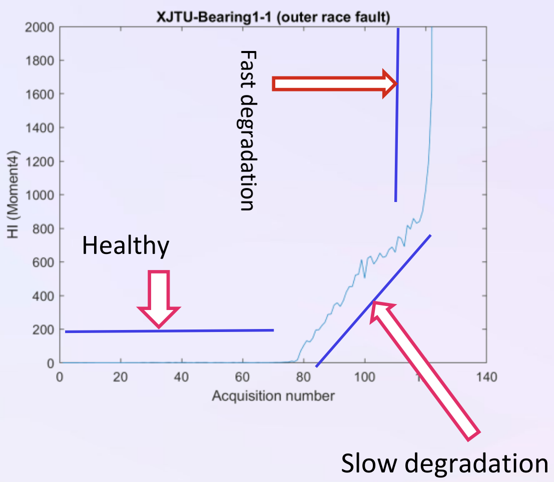


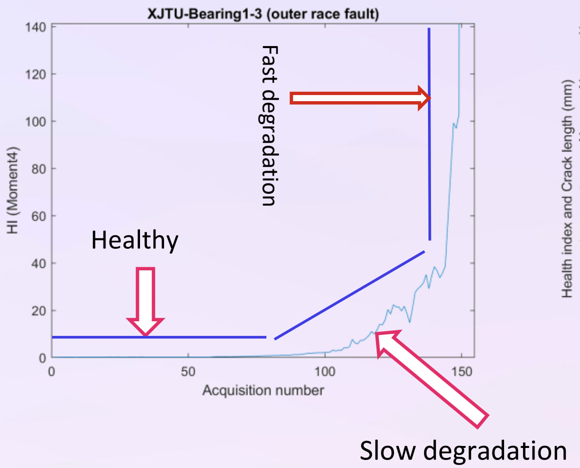


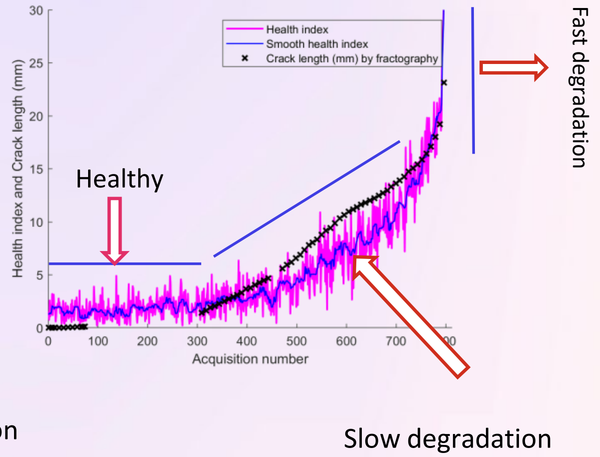
Problem formulation

We have collected a lot of signal (degradation trend).

How can we model these trends for use in health assessment and prognostics?

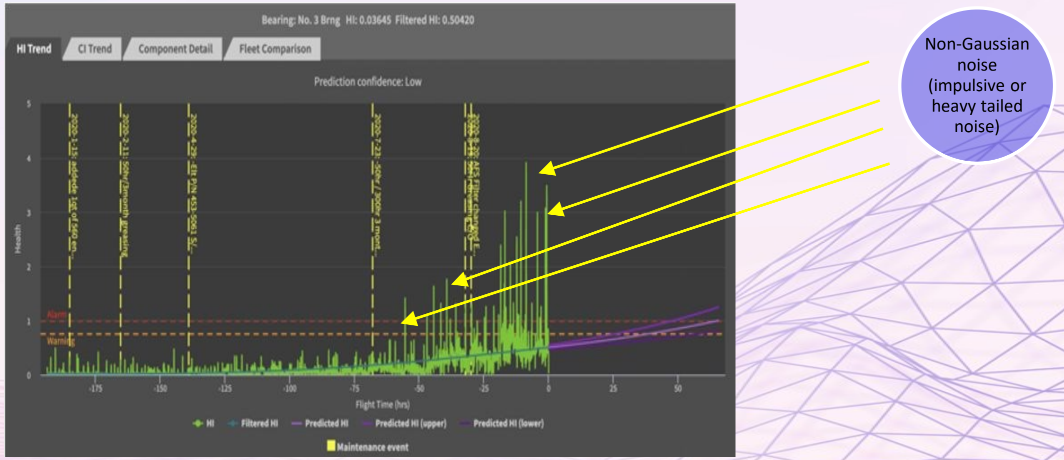






Challenges

- Non-monotonic
- Non-stationary
- Heavy-tailed noise
- Seasonal trend
- Short or long term dependence



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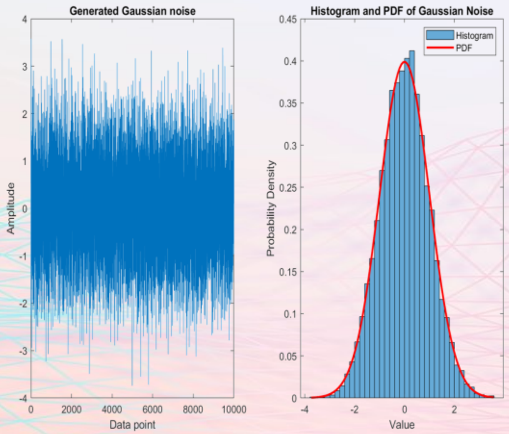
The purpose of this research

This work focuses on developing a switching model by considering non-Gaussian noise (heavy-tailed noise).

Non-Gaussian noise

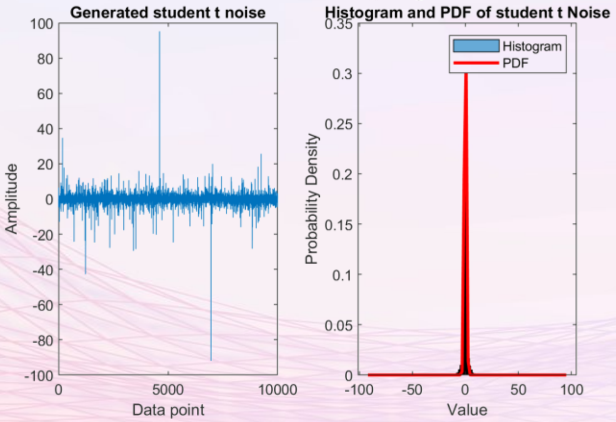
Gaussian noise

Gaussian noise is random variation with a probability distribution following a Gaussian (normal) distribution.



Non-Gaussian noise

Non-Gaussian noise refers to random variation that does not follow a Gaussian (normal) distribution, exhibiting characteristics such as skewness, heavy tails, or multimodality

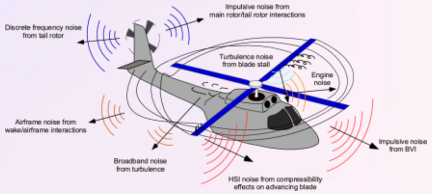


Heavy tails noise source

Mining industry → Falling ore

Aviation → Turbulence

Wind turbine



Idea and methodology

Switching model

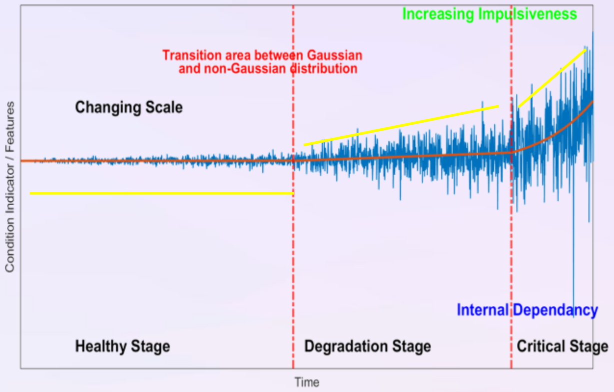
Healthy stage	Slow degradation stage (degradation stage)	Fast degradation stage (critical stage)
Constant	Linear growing function	Exponential or polynomial function

Switching Kalman filter (Dynamic Bayesian approach)

Advantages
- Fast and low computat ion cost
- Probabilistic

Disadvantages
- Can not tolerated heavy tailed noise

Degradation data



Changing the behavior from one stage to another stage

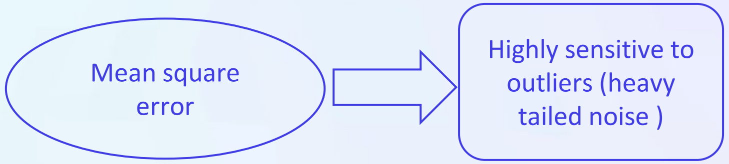
Heavy- tailed noise

Robust Switching extended Kalman filter

- Switching Extended Kalman filter (SEKF)
- Maximum correntropy criterion is used to drive robust SEKF against heavy tailed noise

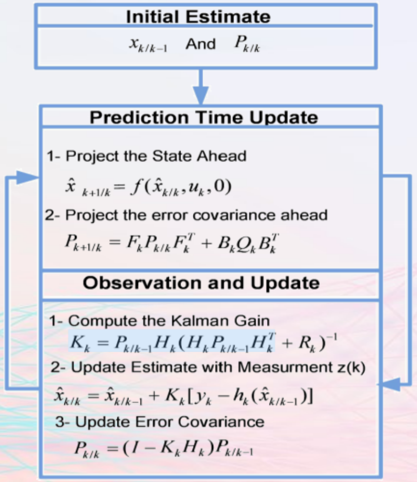
Theorem

Classic Extended Kalman filter



$$x_k = f_{k-1}(x_{k-1}, u_{k-1}, w_{k-1})$$
$$y_k = h_k(x_k, v_k)$$

$$F_k = \frac{\partial f}{\partial x}|_{x_{k-1}}$$
$$H_t = \frac{\partial h}{\partial x}|_{x_k}$$



Maximum Correntropy criterion

Given two random variables X, Y ∈ ℝ with joint distribution function

$F_{XY}(x, y)$ correntropy is defined by:

$$V(X, Y) = E[\kappa(X, Y)] = \int \kappa(x, y)\, dF_{XY}(x, y)$$

$$k(x, y) = G_\sigma(e) = exp(\frac{-e^2}{2\sigma^2})$$

$$\hat{V}(X, Y) = (\frac{1}{N}) \sum_{i=1}^{N} G_\sigma(e(i))$$

$$V(X, Y) = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2^n \sigma^{(2n)} n!)} E[(X - Y)^{(2n)}]$$

- Robustness to Non-Gaussian Noise
- Better Handling of Non-Stationary Processes
- Improved Performance with Heteroscedastic Noise

Maximum Correntropy criterion extended Kalman filter

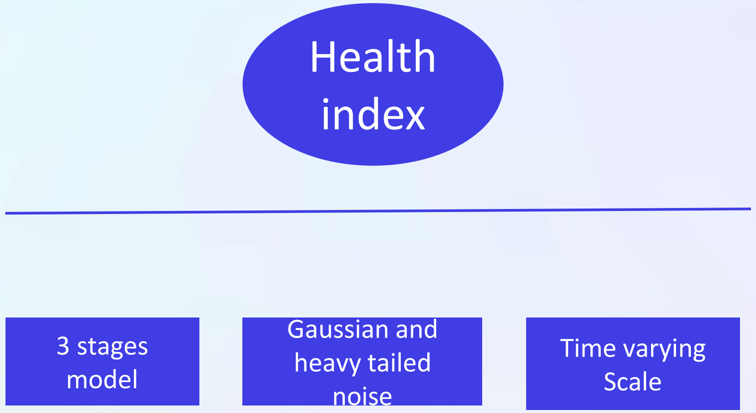
$$J_{MC} = G_\sigma(\|y_k - h(x_k)\|_{R_k^{-1}} + G_\sigma(\|x_k - f(\hat{x}_{k-1|k-1})\|_{R_{k|k-1}^{-1}}$$

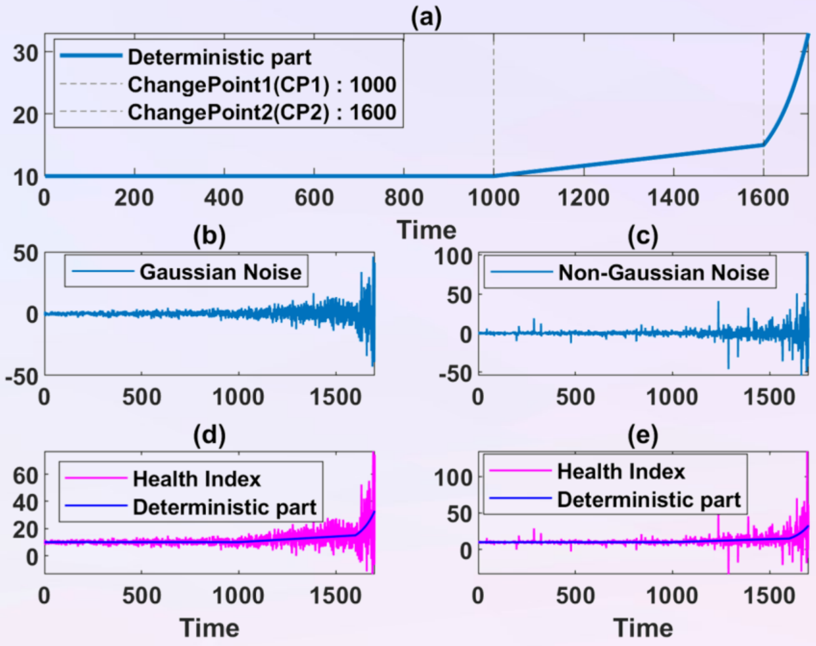
where, $G_\sigma(u) = \exp(-\frac{u^2}{2\sigma^2})$

$$\frac{\partial J_m}{\partial \hat{x}_{k|k}} = 0 \qquad \lambda_k = G_\sigma(\|y_k - h(\hat{x}_{k|k-1})\|_{R_k^{-1}}$$

$$K_k = \hat{P}_{k|k-1} \lambda_k H_k^T (H_k \hat{P}_{k|k-1} \lambda_k H_k^T + R_k)^{-1}$$

Simulation of Health index





Synthetic health index degradation model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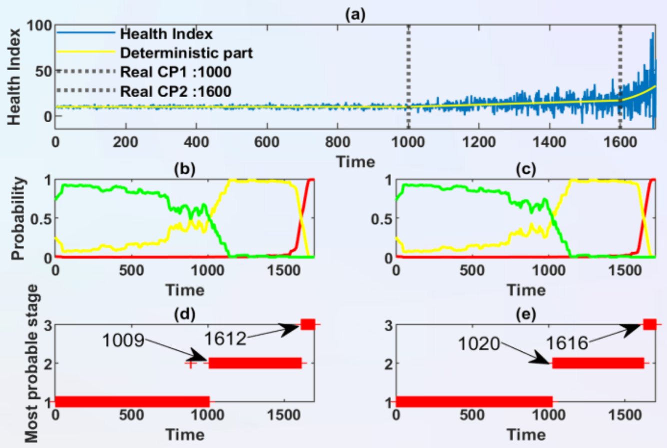
Result for simulated health index

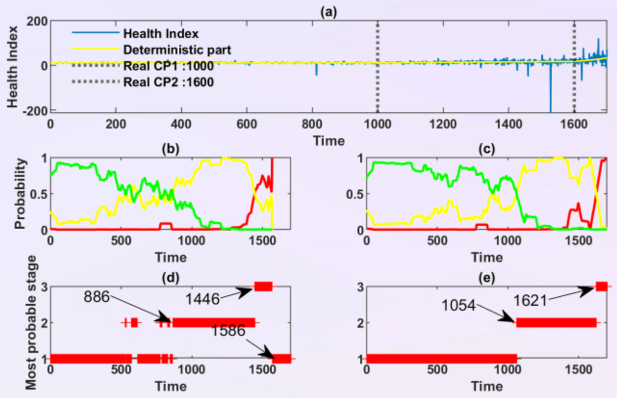
Gaussian



Detection of the stages in the presence of Gaussian noise, (a) HI, (b) probability of stages performed by SKF, (c) probability of stages performed by SMCKF, (d) most probable stages based on the implementation of SKF, (e) most probable stages based on the implementation of SMCKF.

Both the classic and robust methods work well

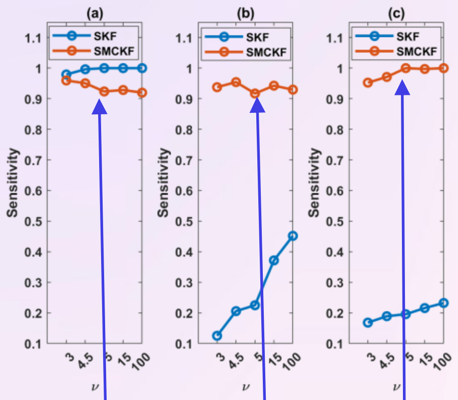
Non-Gaussian



Detection of the stages in the presence of non-Gaussian noise, (a) HI, (b) probability of stages by SKF, (c) probability of stages by SMCKF, (d) most probable stages based on the implementation of SKF, (e) most probable stages based on the implementation of SMCKF.

The robust method works well; however, the performance of the classic approach is affected by non-Gaussian noise

Sensitivity analysis for 100 simulated health index in presence of different level of non-Gaussian noise

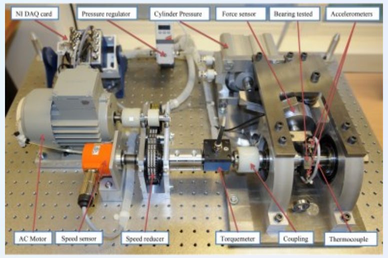


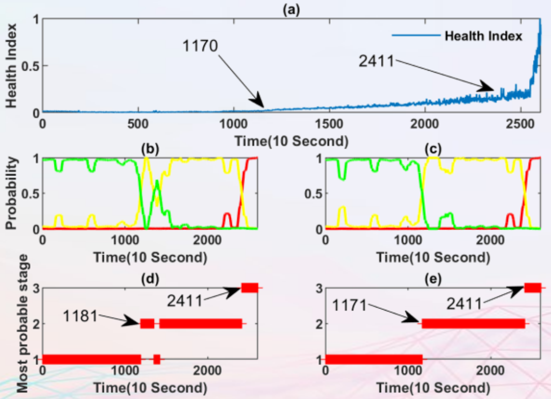
Sensitivity analysis, (a) health stage, (b) degradation stage, (c) critical stage.

The sensitivity of proposed approach is remain stable for different level of non-Gaussian noise

Result for real case study

PRONOSTIA (FEMTO) data set

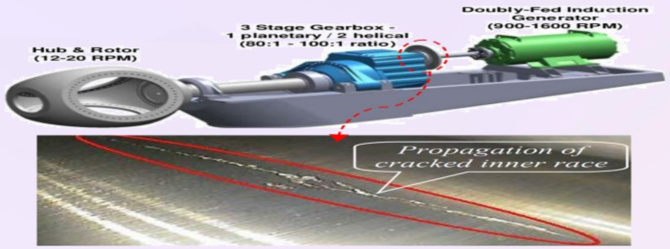


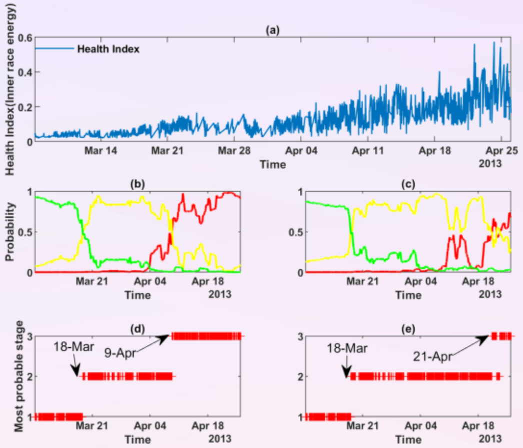


Segmentation of the FEMTO data set, (a) HI, (b) probability of stage by SKF, (c) probability of stage by SMCKF, (d) most probable stages based on the implementation of SKF, (e) most probable stages based on the implementation of SMCKF.

Both the classic and robust methods work well

Wind turbine data set





Segmentation of the Wind turbine data set, (a) HI, (b) probability of stage by SKF, (c) probability of stage by SMCKF, (d) most probable stages based on the implementation of SKF, (e) most probable stages based on the implementation of SMCKF.

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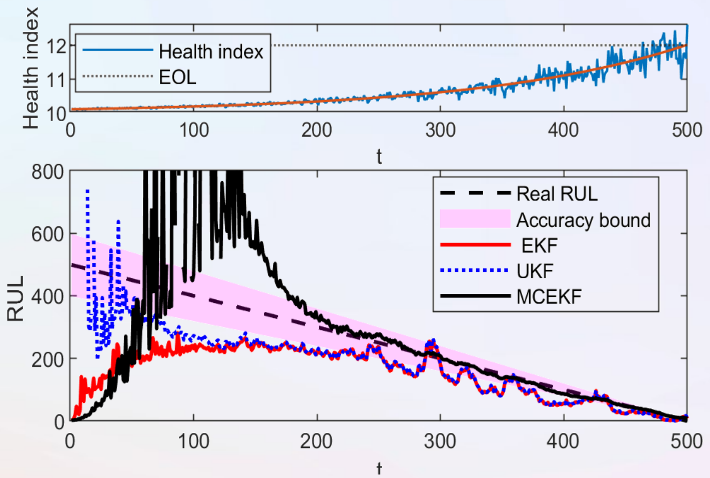
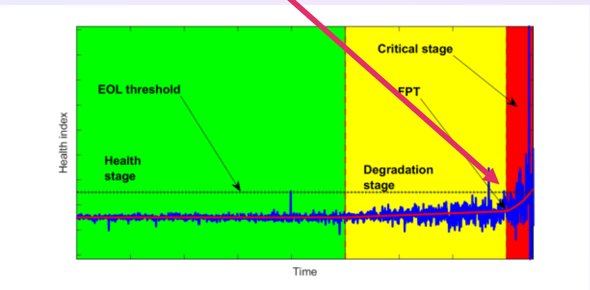
Prediction results for simulated health index

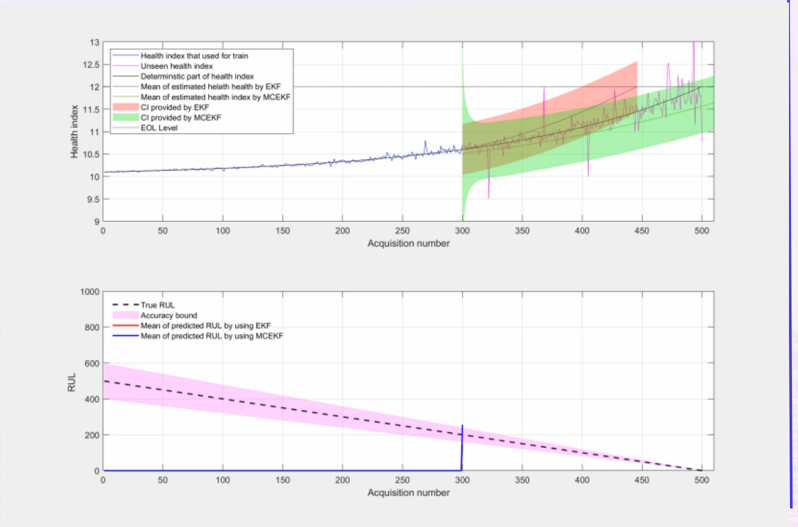
Gaussian noise



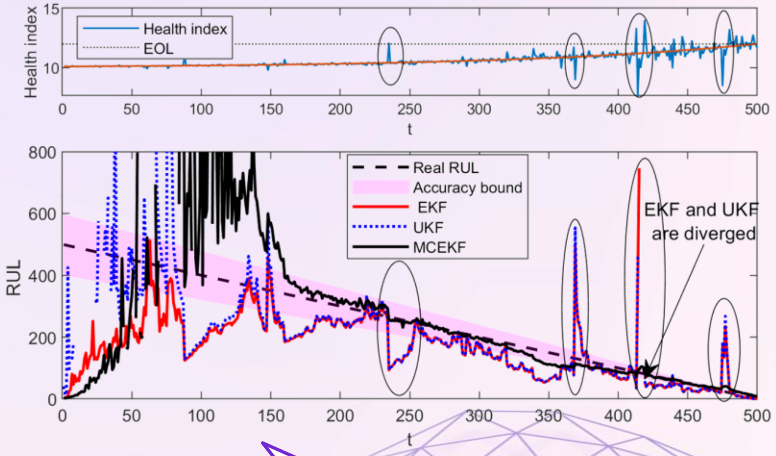
Both the classic and robust methods work well

When the last stage is detected, the procedure of predicting RUL based on defined RUL is started





Non-Gaussian noise



The robust method works well; however, the performance of the classic approach is affected by non-Gaussian noise

Conclusion

- Maximum correntropy criterion Switching extended Kalman filter is proposed.
- The proposed approach is used to health assessment and predicted RUL
- The method assumes the non-Gaussian distribution and time-varying characteristics of the data.
- Efficiency is verified for simulated data sets.
- Two benchmark real data sets have been used to validate the procedure.

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Using long-term condition monitoring data with non-Gaussian noise for online diagnostics

Hamid Shiri [a,*], Pawel Zimroz [a], Jacek Wodecki [a], Agnieszka Wyłomańska [b], Radosław Zimroz [a], Krzysztof Szabat [c]

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Data-driven segmentation of long term condition monitoring data in the presence of heavy-tailed distributed noise with finite-variance

Hamid Shiri [a,*], Pawel Zimroz [a], Jacek Wodecki [a], Agnieszka Wyłomańska [b], Radoslaw Zimroz [a]

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Estimation of machinery's remaining useful life in the presence of non-Gaussian noise by using a robust extended Kalman filter

Hamid Shiri [a,*], Pawel Zimroz [a], Agnieszka Wyłomańska [b], Radosław Zimroz [a]

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