ESTIMATION OF GAS TURBINES GRADUAL DETERIORATION THROUGH A DEMPSTER-SCHAFER BASED FUSION METHOD

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- Description of the diagnostic problem
- Fusion of Gradual Deterioration Estimations
  - o The General Scheme
  - o Inside the Dempster-Schafer fusion technique
- Application on a Turbofan Engine
- Method evaluation
  - o Health parameter estimation
  - o Diagnostic accuracy assessment
  - o Reliability of diagnosis
- Summary - Conclusions

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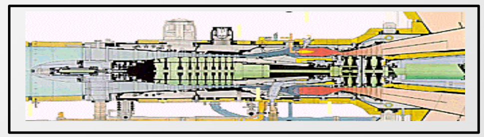
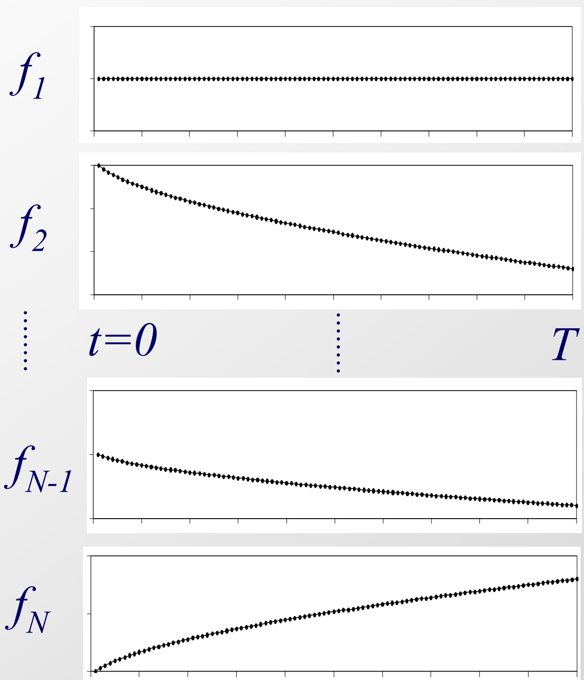
Description of the diagnostic problem

u (operating point)
f (health condition)

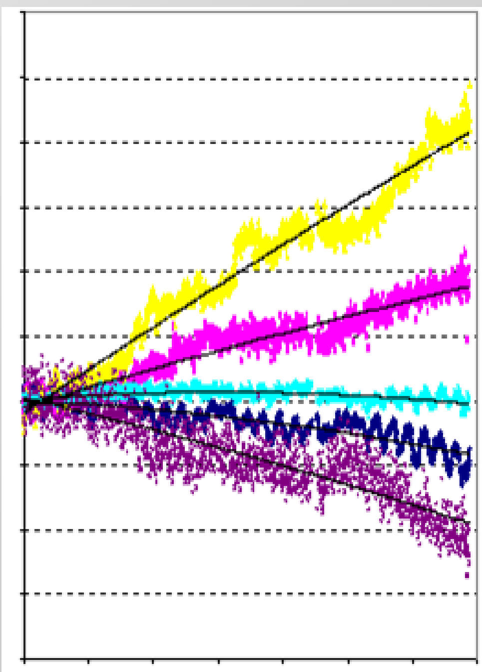


Y (measurements)



Engine gradual deterioration (represented by a health parameters drift), cause a corresponding measurement drift.

Given the series of measurements the goal is to estimate the health parameters value over time.



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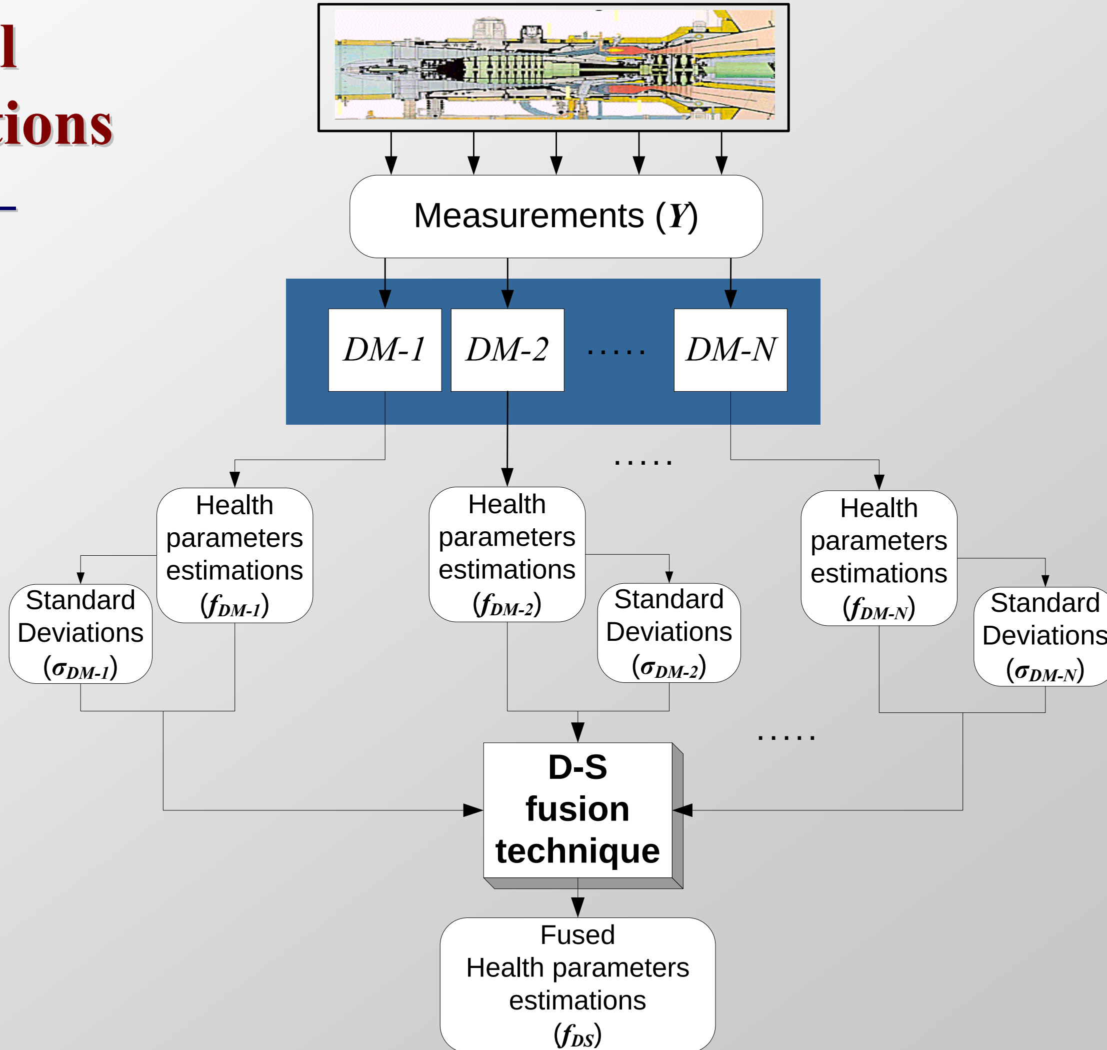
Fusion of Gradual Deterioration estimations

-The general scheme–

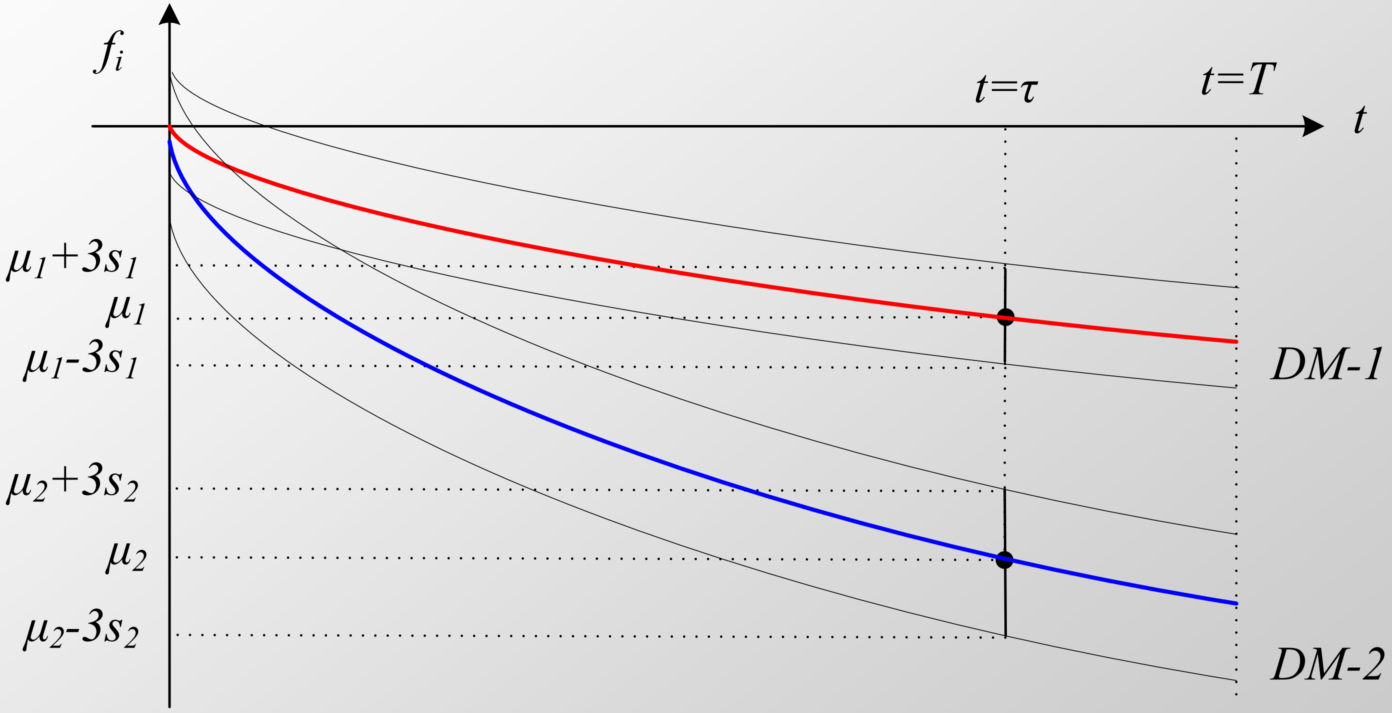
Individual diagnostic methods provide health parameters estimations.

The D-S fusion technique combines these estimations into a more accurate and reliable estimation



Fusion of Gradual Deterioration estimations

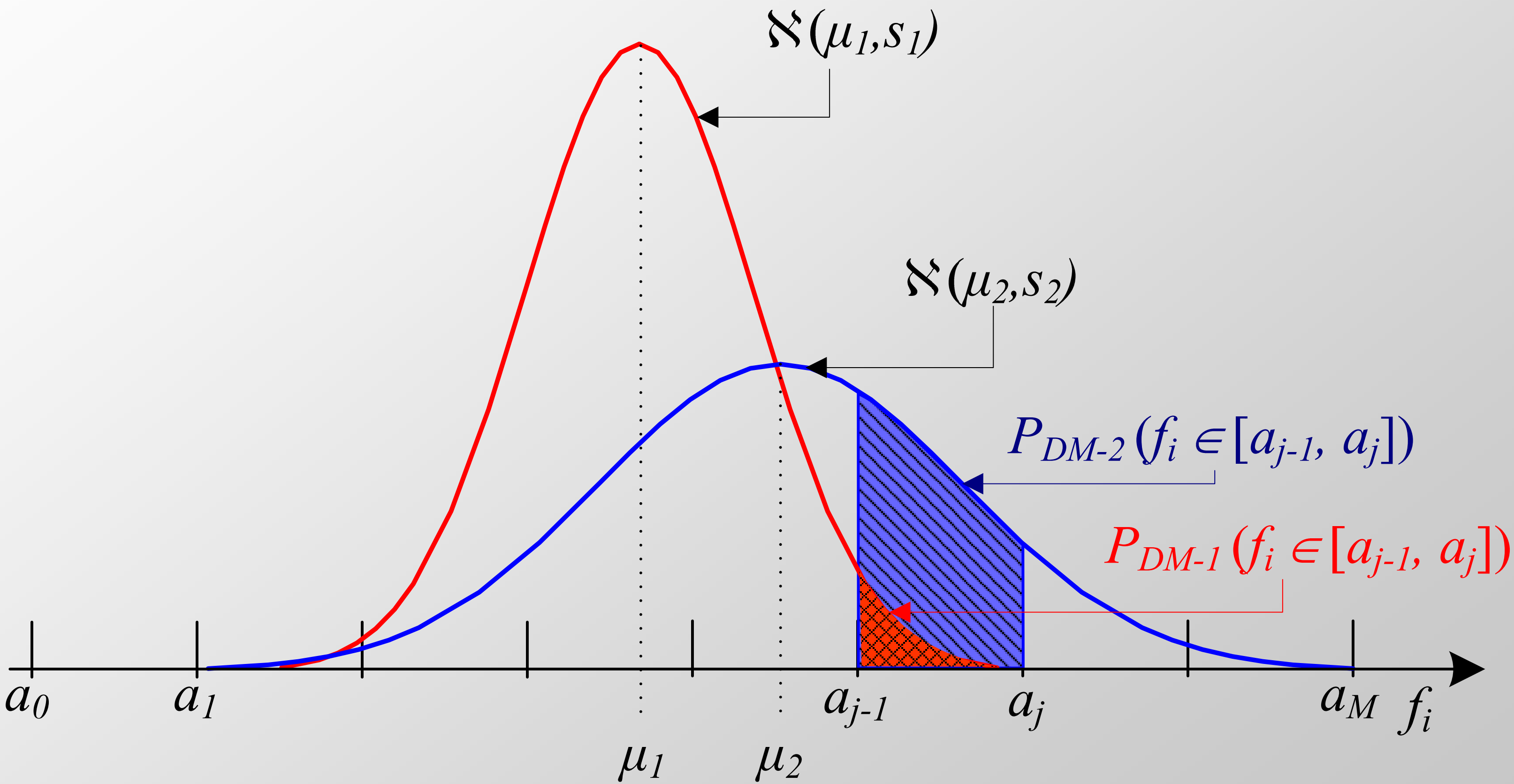
-Inside the Dempster-Schafer fusion technique–



Estimation of f_i value, at point t=τ, given the estimations provided by the independently acting methods *DM-1* and *DM-2*

Fusion of Gradual Deterioration estimations

-Inside the Dempster-Schafer fusion technique–



Basic Principles of Dempster-Schafer theory

Dempster–Schafer theory: $m : \Theta \rightarrow [0,1],\ \mu\varepsilon\ m(\varnothing) = 0\ \kappa\alpha\iota \sum_{x \in \Theta} m(x)$

Probability theory: $P : \delta \rightarrow [0,1],\ \mu\varepsilon\ P(\varnothing) = 0\ \kappa\alpha\iota \sum_{x \in \delta} P(x)$

$$\boxed{m_{DM-i}\left(f_i \in \left[-\alpha, +\alpha\right]\right) = P_{DM-i}\left(f_i \in \left[-\alpha, +\alpha\right]\right)}$$

The mass m_{DM-i} expresses our belief the f_i value lies within the interval [-α, +α], regarding the results of *DM-i* diagnostic method

Basic Principles of Dempster-Schafer theory

Dempster's combination rule

$m_{DM\text{-}1}$

$m_{DM\text{-}2}$

$$m_{DM\text{-}1} \oplus m_{DM\text{-}2}(x) = \frac{\sum_{x_1 \cap x_2 = x} m_{DM\text{-}1}(x_1) \cdot m_{DM\text{-}2}(x_2)}{1 - \sum_{y_1 \cap y_2 = \varnothing} m_{DM\text{-}1}(y_1) \cdot m_{DM\text{-}2}(y_2)}$$

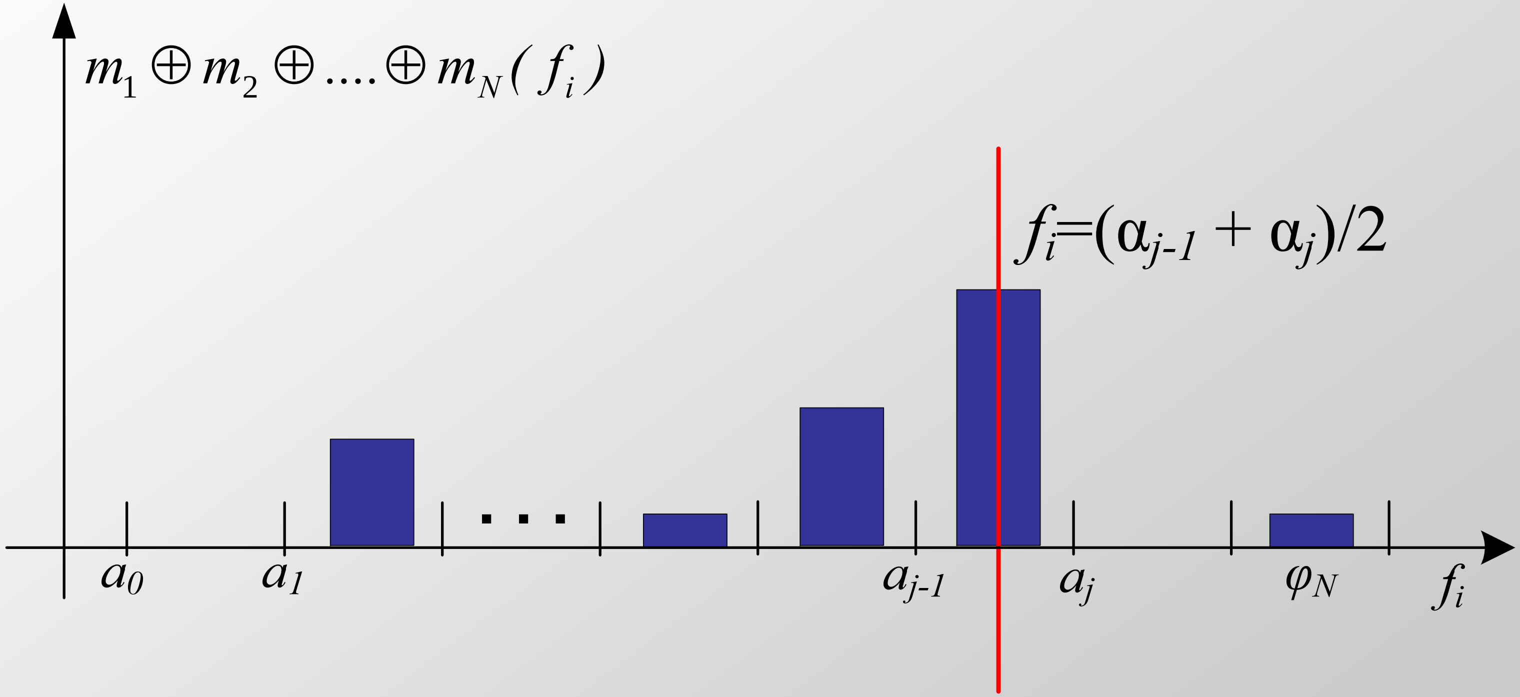
$$x, x_1, x_2, y_1, y_2 \longrightarrow f_i \in [\alpha, b]$$

Generalized combination rule for N sources of information:

$$m_1 \oplus m_2 \oplus \ldots. \oplus m_N(x) = \frac{m_1(x) \cdot m_2(x) \cdot \ldots \cdot m_N(x)}{1 - \sum_{y_1 \cap y_2 \cap \ldots \cap y_N = 0} m_1(y_1) \cdot m_2(y_2) \cdot \ldots \cdot m_N(y_M)}$$

Fusion of Gradual Deterioration estimations

-Diagnostic criterion / Health parameter estimation–



The estimated health parameter value is the mean value of the interval tied with the maximum combined mass

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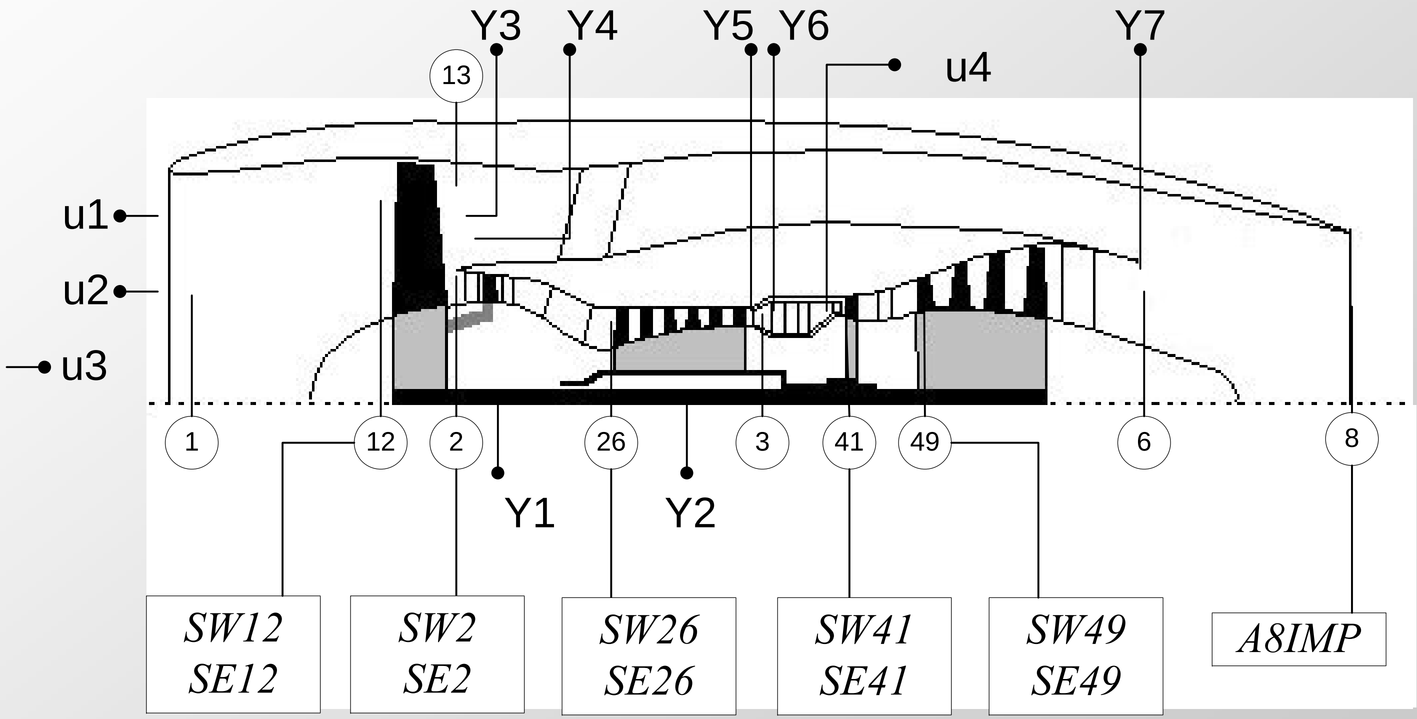
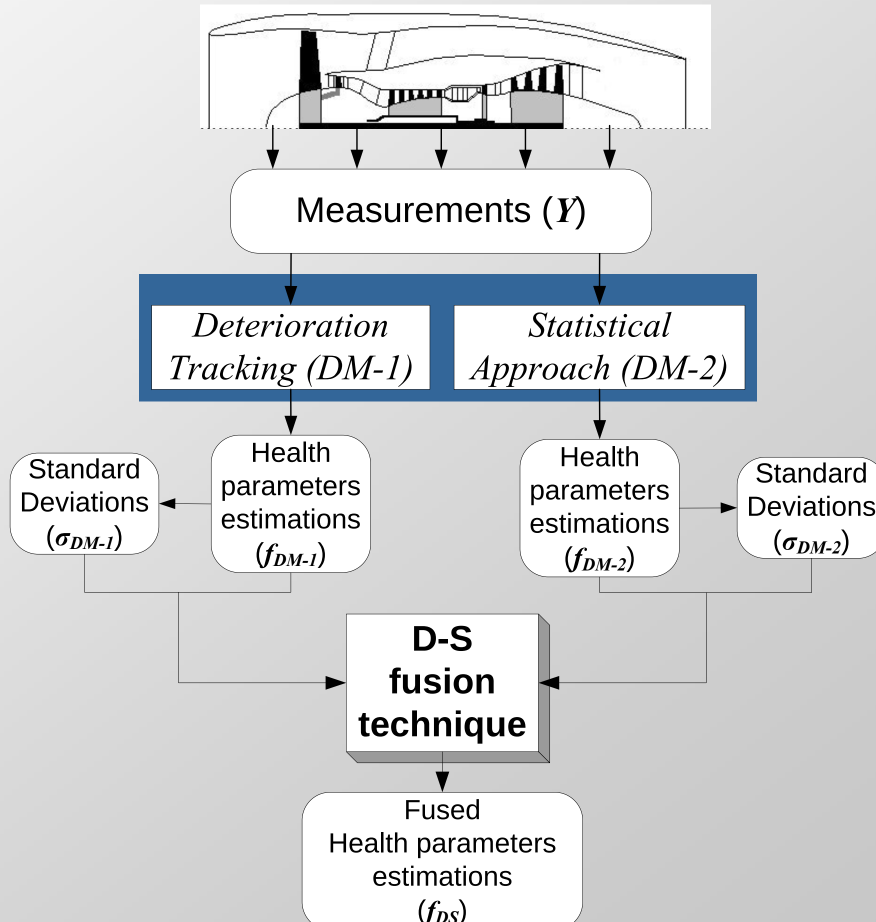
Application on a Turbofan engine



Twin spool, high-by-Pass ratio, turbofan engine used as a test case

Application on a Turbofan engine

- **Five simulated data sets have been considered, representing realistic fault case scenarios.**
- **Each data set contains a series of simulated noisy measurements representing deviations of one or more health parameters due to fault.**



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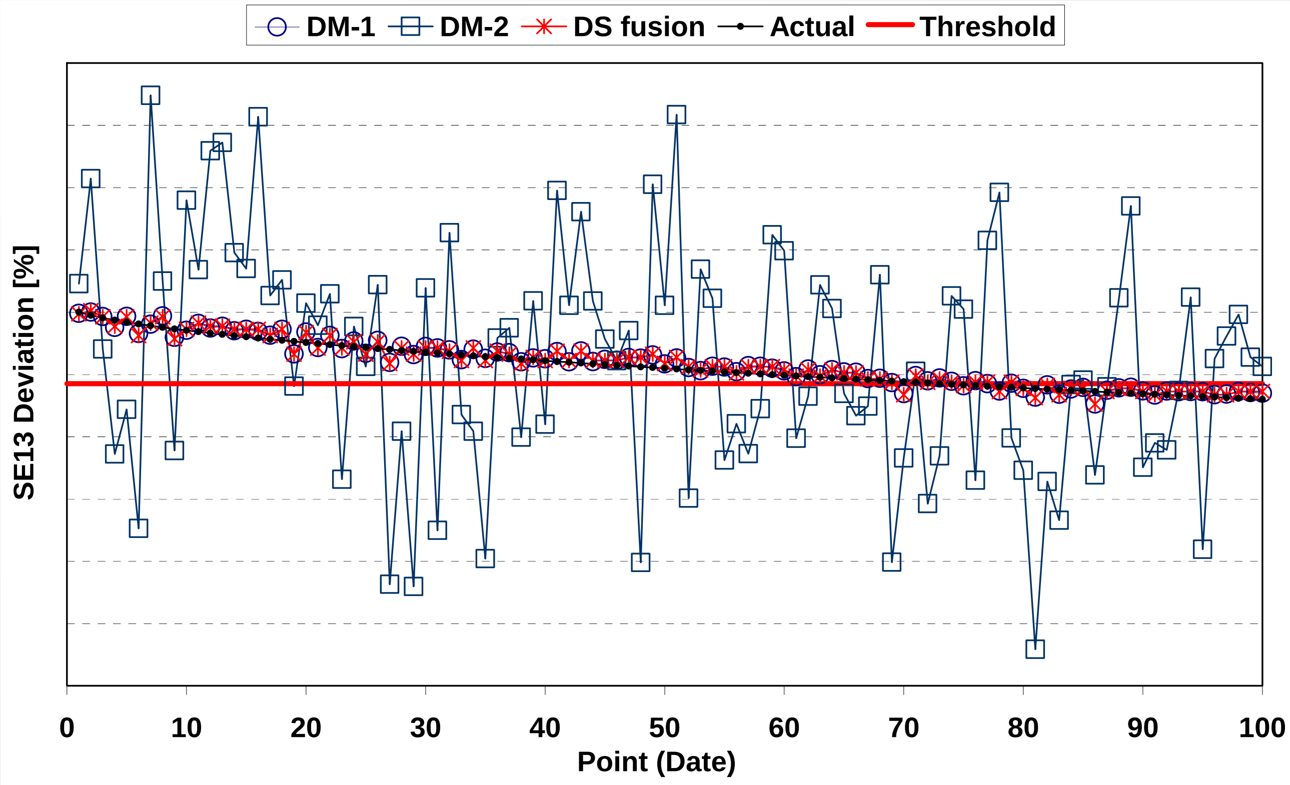
Method Evaluation

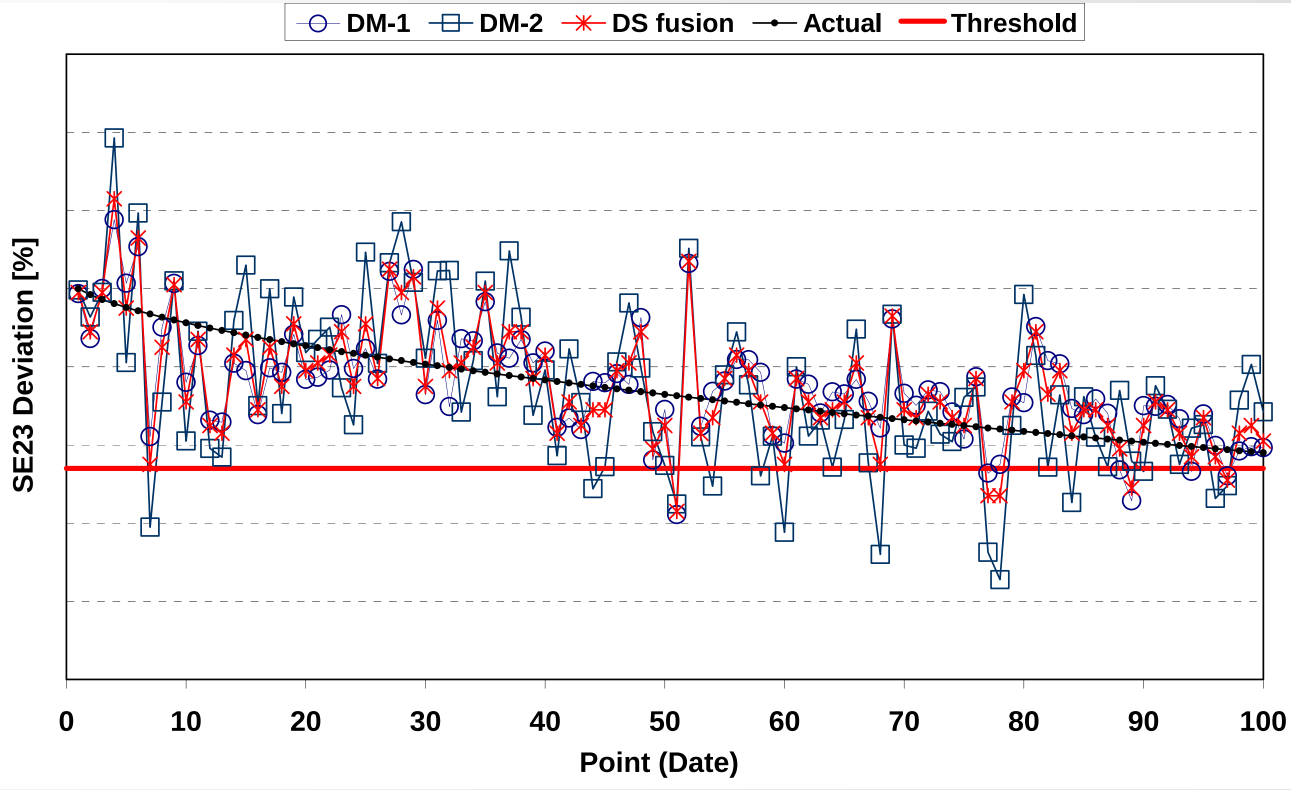
Health parameters estimations



DM-1 estimations perform smaller scattering, so does the proposed fusion method

Method Evaluation

Health parameters estimations



Both DM-1 and DM-2 estimations perform large scattering; the D-S fusion technique reduces the estimations scattering

Method Evaluation

Diagnostic accuracy assessment

Health Parameter	test case 1			test case 2			test case 3			test case 4			test case 5		
	DM-1	DM-2	FUSION	DM-1	DM-2	FUSION	DM-1	DM-2	FUSION	DM-1	DM-2	FUSION	DM-1	DM-2	FUSION
SW12	0.443	0.437	0.434	0.488	0.461	0.471	0.473	0.460	0.458	0.437	0.430	0.425	0.440	0.433	0.431
SE13	0.475	3.106	0.486	0.419	3.807	0.424	0.507	3.419	0.495	0.560	3.205	0.548	0.523	3.356	0.510
SW2	0.544	3.144	0.569	0.638	3.687	0.675	0.709	3.596	0.703	0.647	3.340	0.639	0.729	3.468	0.716
SE23	0.669	1.163	0.719	0.815	1.140	0.837	0.933	1.130	0.916	0.818	1.094	0.815	0.911	1.147	0.908
SW25	0.435	2.976	0.453	0.486	3.668	0.496	0.540	3.383	0.548	0.464	3.145	0.472	0.493	3.271	0.499
SE3	0.273	0.533	0.284	0.308	0.545	0.313	0.393	0.534	0.392	0.367	0.535	0.363	0.381	0.516	0.380
SW41	0.344	2.617	0.347	0.334	3.238	0.334	0.362	3.038	0.365	0.319	2.854	0.325	0.344	3.012	0.347
SE42	0.343	1.359	0.347	0.596	1.956	0.600	0.395	1.529	0.405	0.834	1.917	0.830	0.856	1.908	0.850
SW49	0.287	2.416	0.295	0.913	2.737	0.913	0.363	2.674	0.370	1.081	2.243	1.071	1.250	3.514	1.235
SE5	0.395	0.392	0.362	0.530	0.505	0.502	0.877	0.384	0.714	0.778	0.523	0.713	0.758	1.425	0.636
No. of min. scattering	**8**	**0**	**2**	**6**	**1**	**3**	**4**	**1**	**5**	**2**	**1**	**7**	**2**	**0**	**8**

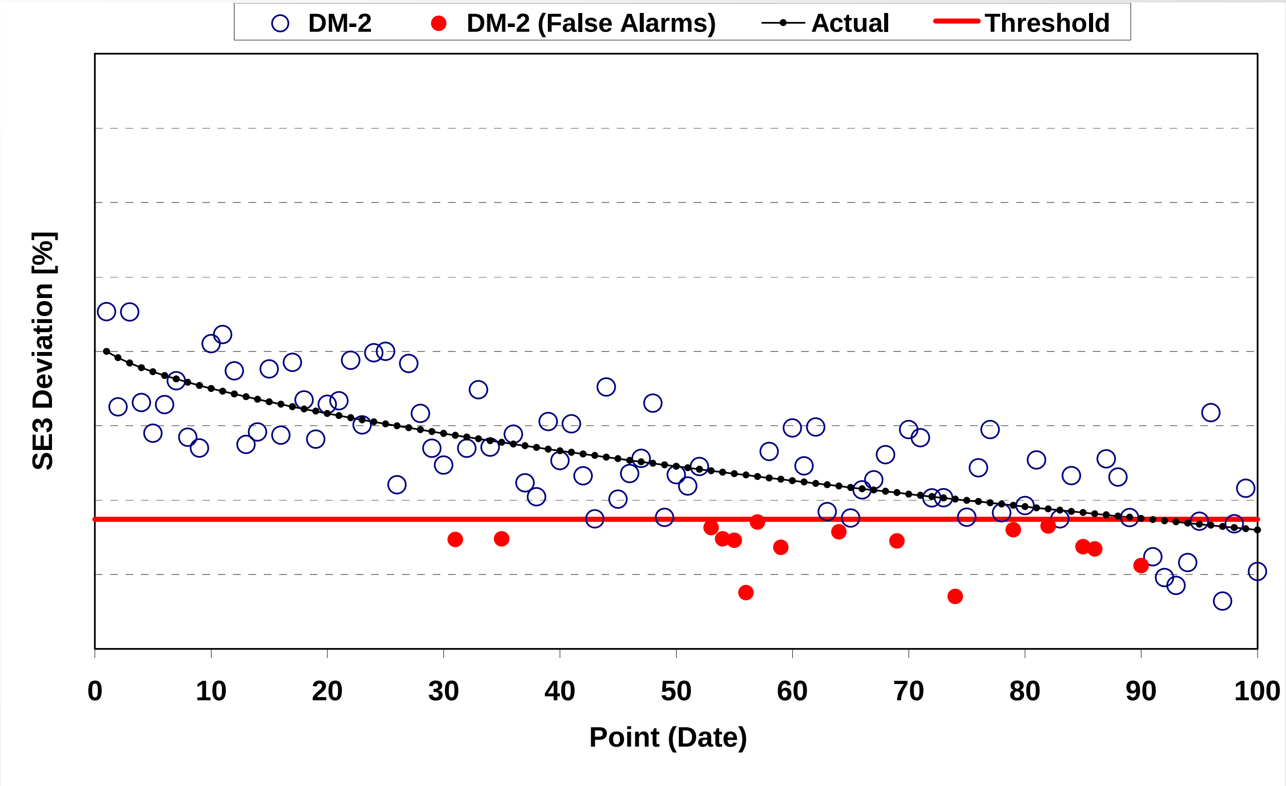
Estimations scattering is quantified through the standard deviation of the estimations:

$$s_{f_i} = \sqrt{\frac{\sum_{j=1}^{n}\left(f_{i,j} - f_{i,j}^{act}\right)^2}{n}}$$

The proposed fusion technique leads to a more accurate estimation of the health parameters

Method Evaluation

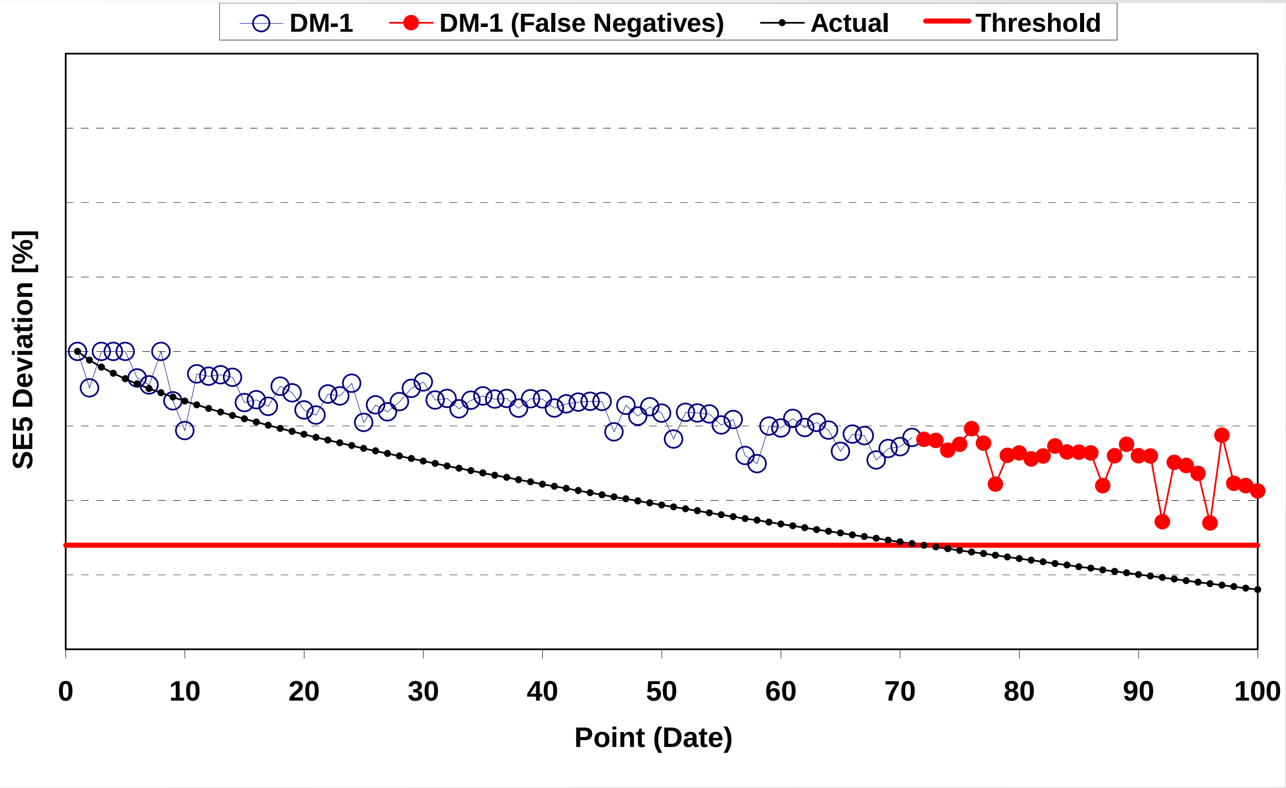
Reliability of diagnosis



False Alarms: The estimated health parameters deviations exceed the fault threshold limits, while the actual deviation lies within these threshold limits.

Method Evaluation

Reliability of diagnosis



False Negatives: The estimated deviations lie within the threshold limits, although the actual deviation of one or more health parameters exceeds these limits.

Method Evaluation

Reliability of diagnosis

Test case	*DM-1*		*DM-2*		*FUSION*	
	Alarms	Negatives	Alarms	Negatives	Alarms	Negatives
1	0.00%	0.50%	16.00%	1.75%	0.00%	0.75%
2	0.88%	0.50%	24.38%	1.63%	0.75%	0.50%
3	0.25%	1.38%	20.25%	1.63%	0.38%	1.13%
4	0.88%	7.75%	26.50%	4.25%	0.88%	7.25%
5	2.83%	1.92%	28.45%	4.94%	2.99%	1.77%
overall	**2.68%**	**1.98%**	**28.07%**	**4.77%**	**2.83%**	**1.83%**

The proposed fusion technique maintains the low levels of false alarms achieved by DM-1, although DM-2 presents very high levels of false alarms.

Additionally, The proposed fusion technique reduces the levels of false negatives.

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Summary - Conclusions

- A Dempster-Schafer based fusion technique allowing identification of degrading gas turbine condition, through fusion of the results of independently acting diagnostic methods, has been presented.
- Application on realistic deterioration scenarios demonstrates that the proposed fusion technique is a fair judge among the results of individual methods, allowing a management of the uncertainty that contradicting diagnostic results and/or diagnosis with large scattering may cause.
- In comparison to independent diagnostic methods results, application of the proposed fusion technique increased, in general, the accuracy and the reliability of the estimations.