Identifying Key Factors in Turbofan Engine Health Degradation using Functional Analysis

A Case Study Using NASA's NC-MAPSS DS02 Data

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Background

Objective: To develop an interpretable method for assessing the state of health in turbofan engines

Key Findings: Identification of critical parameters and flight regime points conducive to effective prognostics

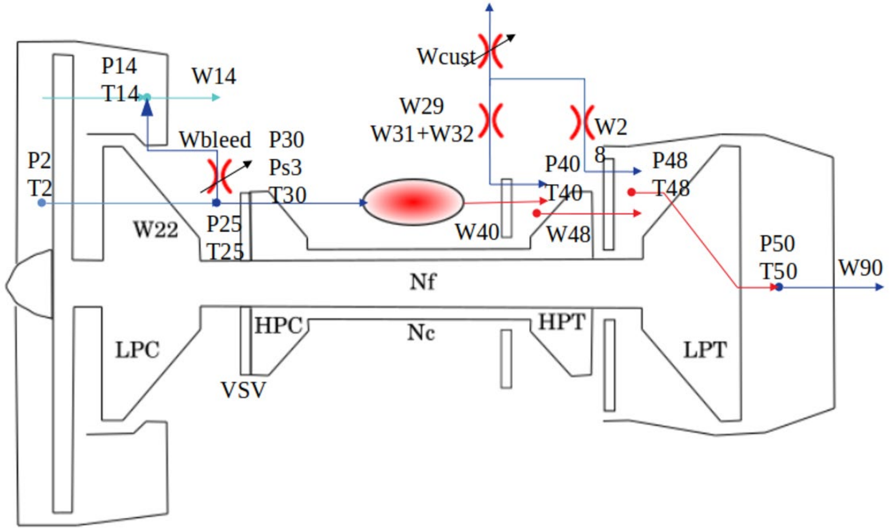
Methodology: Elastic registration, data standardization, and functional principal components analysis (FPCA)

Benchmark: NASA's New Commercial Modular Aero-Propulsion System Simulation (NC-MAPSS) DS02 dataset.

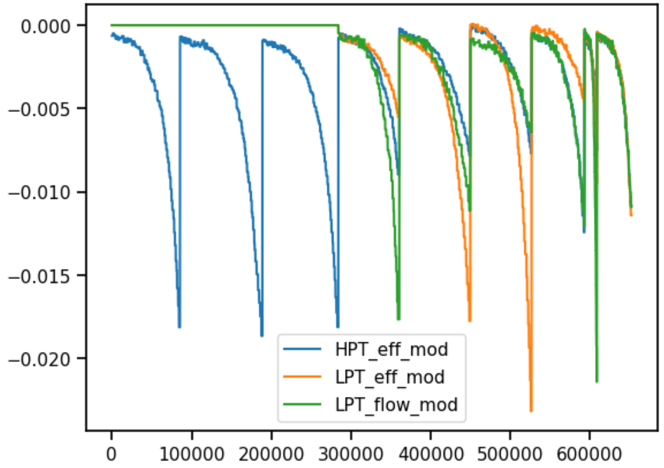
Impact of Prognostics: Implementing accurate and interpretable prognostics can greatly improve safety by enabling early detection of degradation and can reduce maintenance costs through condition-based maintenance strategies.

Background: NASA's NC-MAPSS DS02 Benchmark Dataset

- NASA's NC-MAPSS standardizes aerospace research, providing a reliable basis for developing and validating engine health prognostic models.
- Dataset Details: Features 32 engine-related time-series parameters, aggregated into 26.9 GB of H5 files, capturing real-world flight conditions and turbofan degradation.
- The DS02 dataset contains subset features a specific usage case that simulates three key degradation types: High-Pressure Turbine Efficiency (HPT_eff_mod), Low-Pressure Turbine Efficiency (LPT_eff_mod) and Flow (LPT_flow_mod).



CMAPSS Engine Model Parameters



Chao, M.A., Kulkarni, C., Goebel, K., & Fink, O. (2021). Aircraft engine run-to-failure dataset under real flight conditions for prognostics and diagnostics. Data, 6(1), 5.

Approach

Training Data Folder → SoH Data Folders → .CSV

Testing Data Folder → .CSV

Data Columns [Units]
1) Unit [#]
2) Cycle [#]
3) Flight Condition
4) Health State
5-15) Eff. & Flow Mod
15-47) Engine Parameters

B-Spline Interpolation/General SoH

Monte Carlo Cross-Validation

Fit/Transform { *Elastic Registration*, *Standardization*, *Functional PCA*

Fit/Transform k-NN

Orthogonal Matching Pursuit

↓

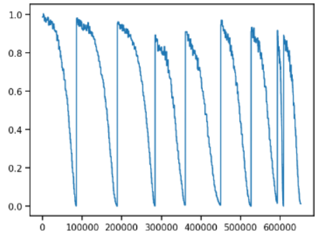
Transform { *Elastic Registration*, *Standardization*, *Functional PCA*

Transform k-NN

↓

State of Health Estimation

Domain Knowledge
- Key Parameters
- Flight Domain Location



General SoH

B-Spline Interpolation and Universal Flight Domain Results

B-Spline Interpolation

$$f(t) = \sum_{i=0}^{n} P_i B_{i,k}(t)$$

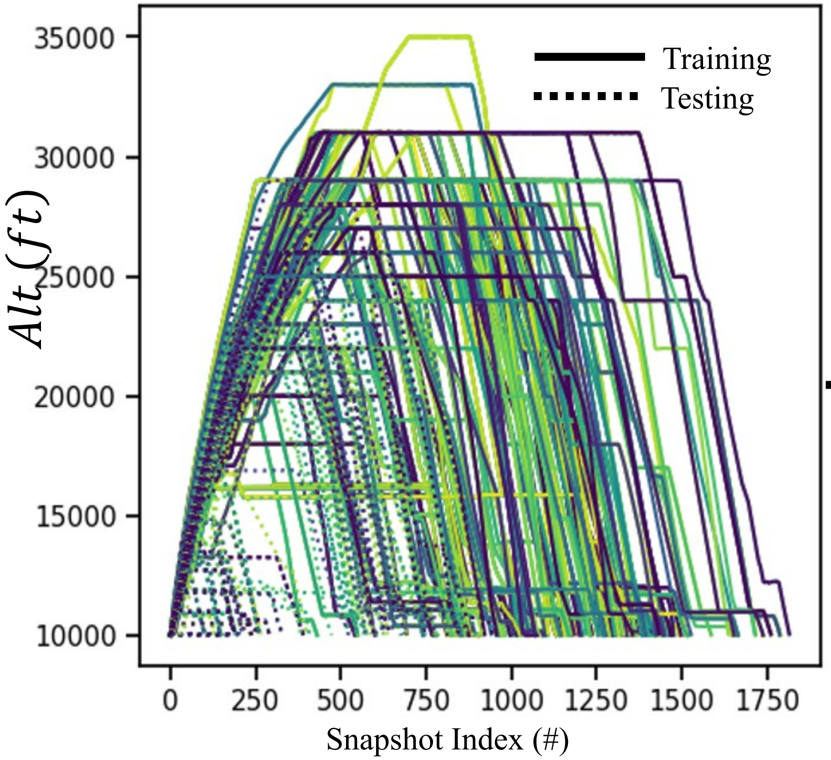
$$B_{i,1}(t) = \begin{cases} 1, & if, t_i \le t \le t_{i+1} \\ 0, & \text{otherwise} \end{cases}$$

$$B_{i,k}(t) = \frac{t - t_i}{t_{i+k-1} - t_i} B_{i,k-1}(t)$$

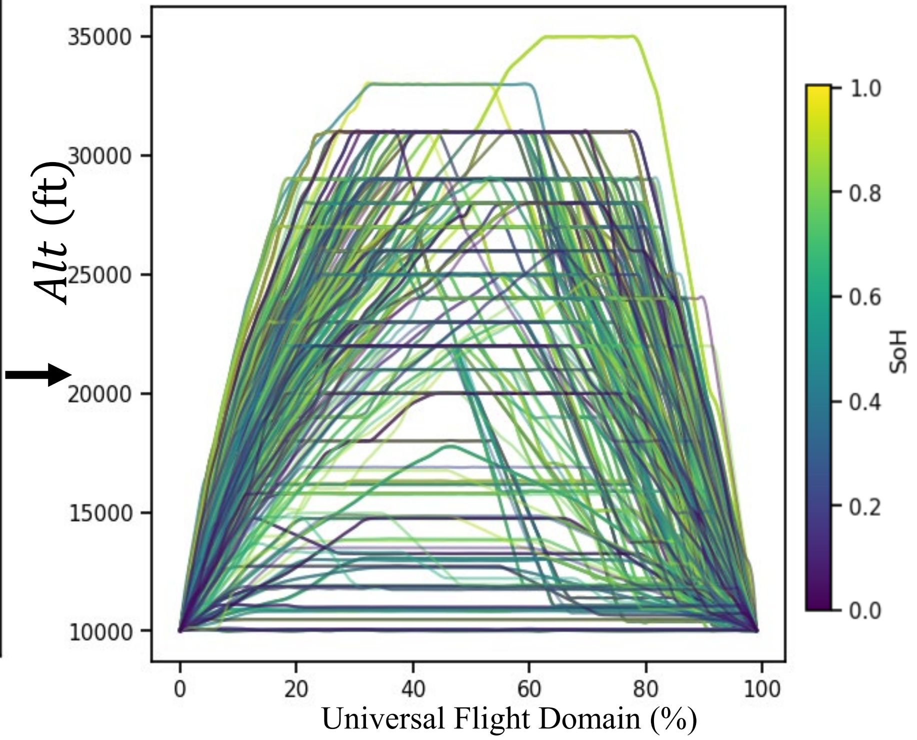
$$+ \frac{t_{i+k} - t}{t_{i+k} - t_{i+1}} B_{i+1,k-1}(t)$$

Finite Difference

$$f'(x) = \frac{f(x+h) - f(x)}{h}$$



Raw data of the altitude time series



B-spline interpolations along a universal flight domain

Elastic Registration and Standardization Results (Equivalency Ratio, Φ)

Elastic Registration

$\gamma^*(t) = argmin_\gamma D\left(f(t), g(\gamma(t))\right)$

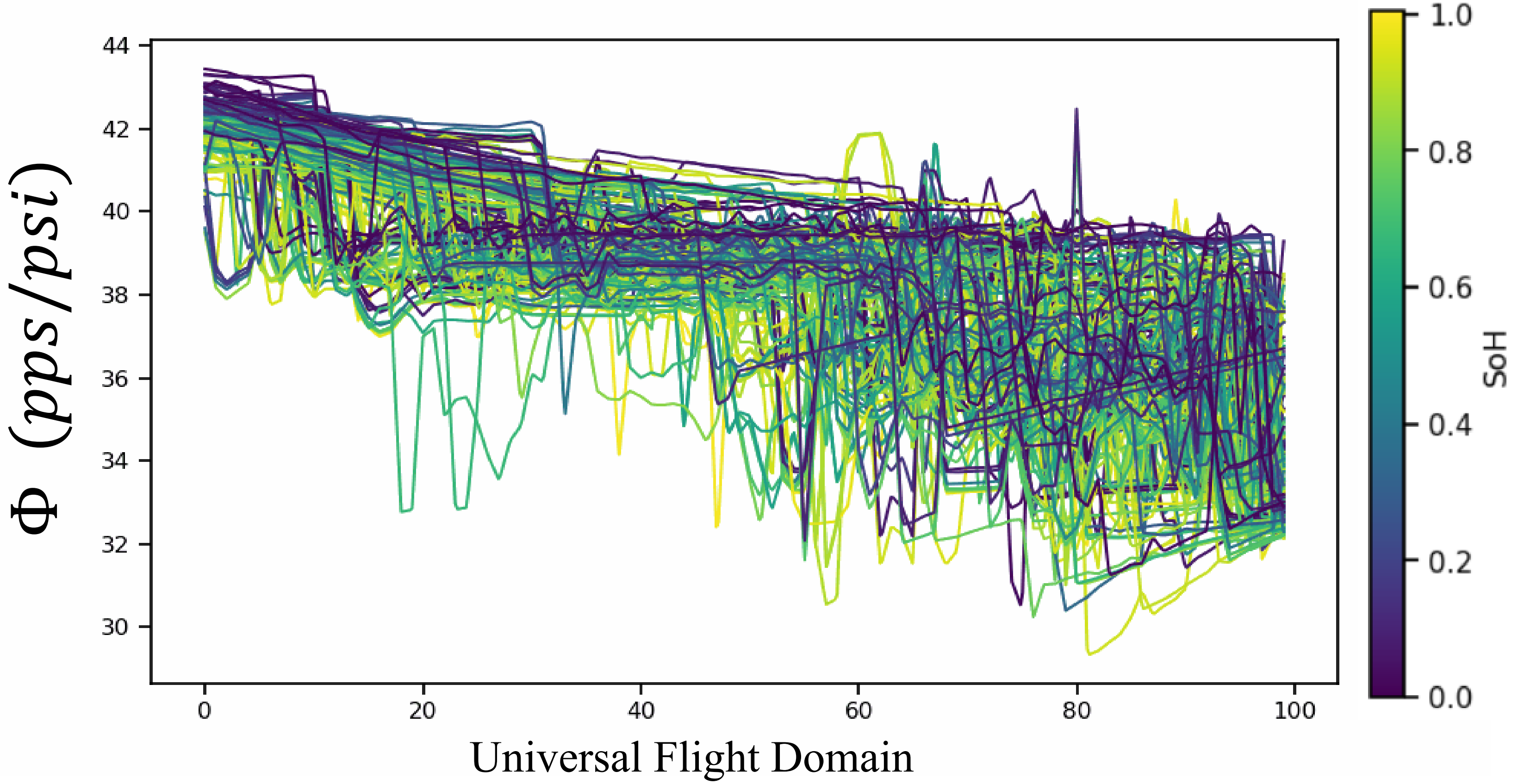
$= argmin_\gamma$

$\int_0^1 || (q(t) - (q_g \circ \gamma))(t)\big) ||^2 \, dt$

Where $(q_g \circ \gamma)(t)$ is the composition of the B-Spline function with the time warping function that minimizes the distance metric.

Standard scaling

$$z = \frac{x-\mu}{\sigma}$$



Resampled raw data using b-spline basis functions being standardized and aligned with the elastic registration method

FPCA Projection Results (Equivalency Ratio, Φ)

Multivariate Principal Component Analysis[

$$\max_{\beta^T\beta=1} \frac{1}{N}\beta^T X^T X\beta$$

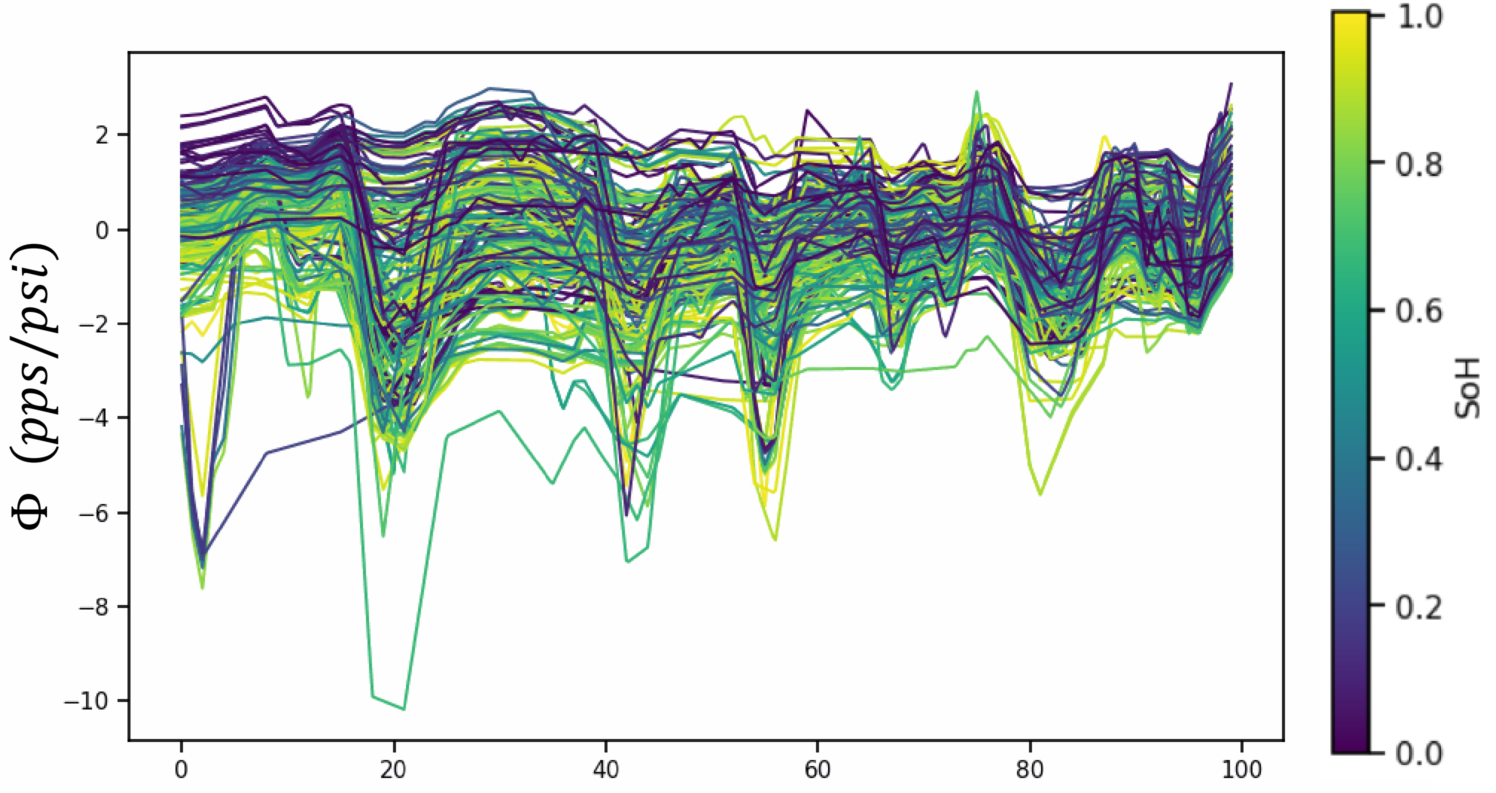
Found solving the eigenvalue problem, $V\beta = \lambda_1\beta$, where $V = \frac{1}{N}(X^T X)$

Functional Principal Component Analysis

$$V_f(s) = \int_T v(s,t)f(t)d(t)$$

Where $v(s,t) = \sum_{i=1}^{N} x_i(s)x_i(t)$

$$\int_T v(s,t)\beta_j(t)d(t) = \lambda_j\beta_j(s)$$



Universal Flight Domain

Resampled Raw Data using B-Spline being converted into the Standardized and Aligned Data

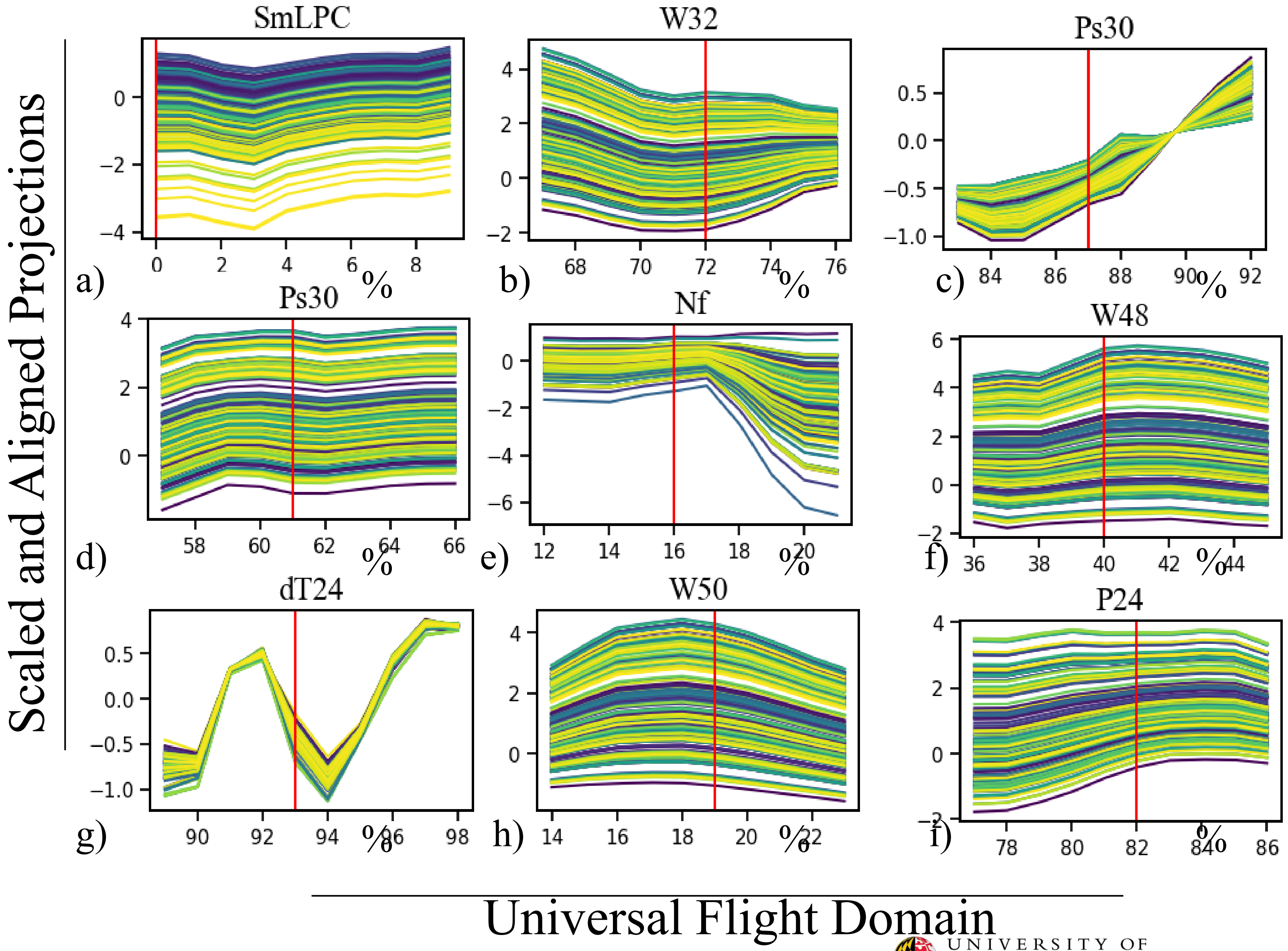
OMP/k-NN Results

K-Nearest Neighbors Regression

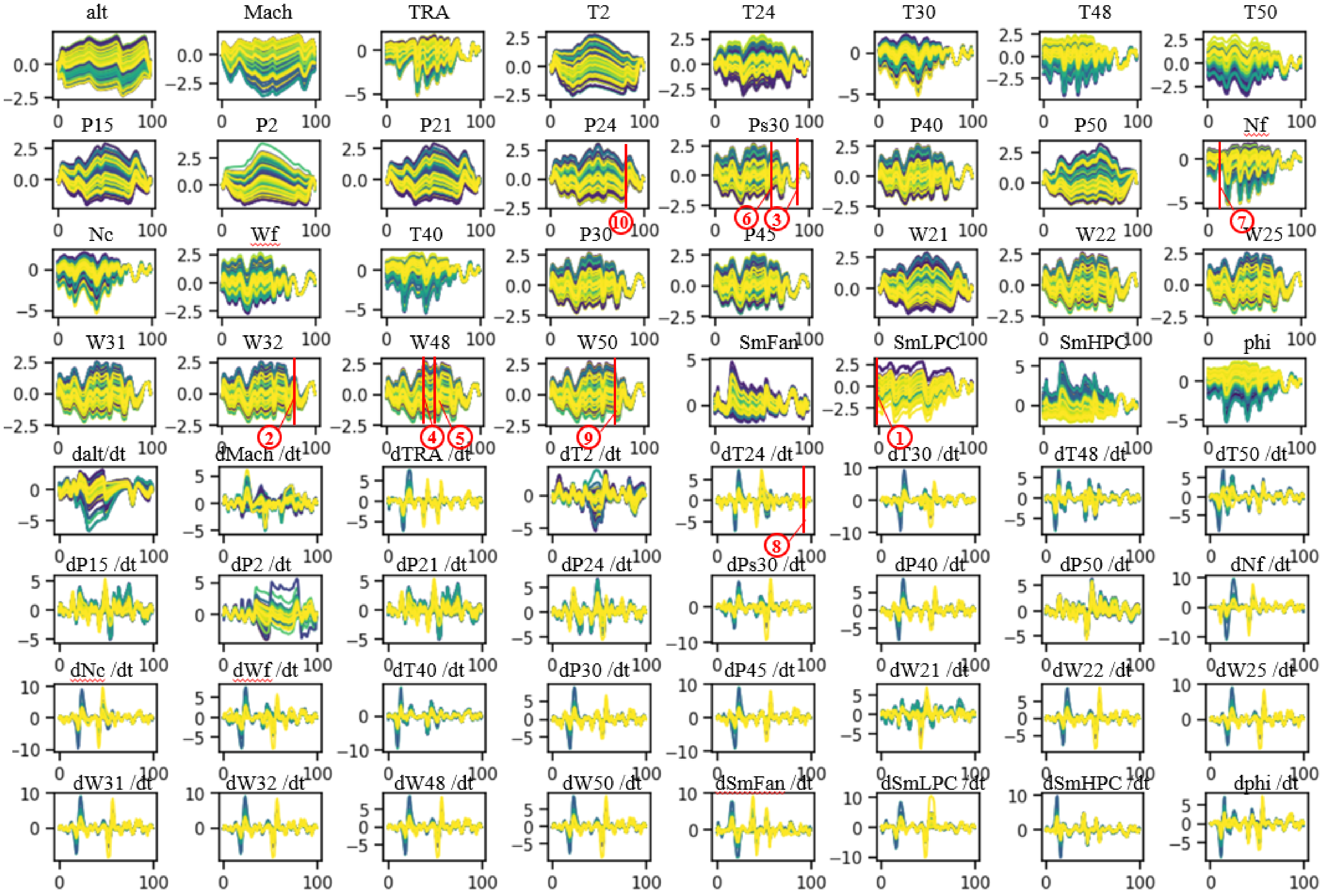
$$\hat{y} = \frac{1}{k}\sum_{i=1}^{k} y_i$$

Orthogonal Matching Pursuit

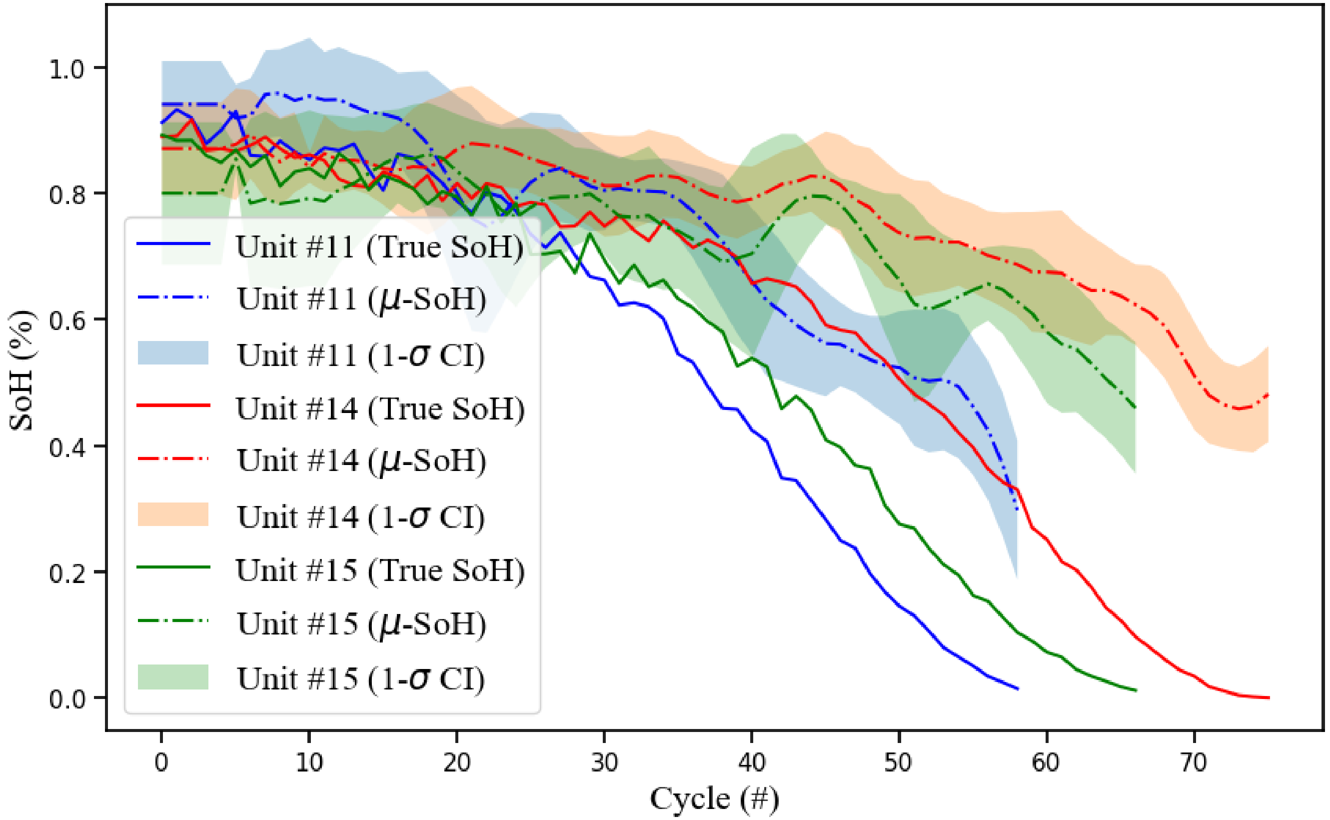
$$argmin_x = ||y - Ax||_2^2$$
$$s.t. ||x||_0 \leq k$$

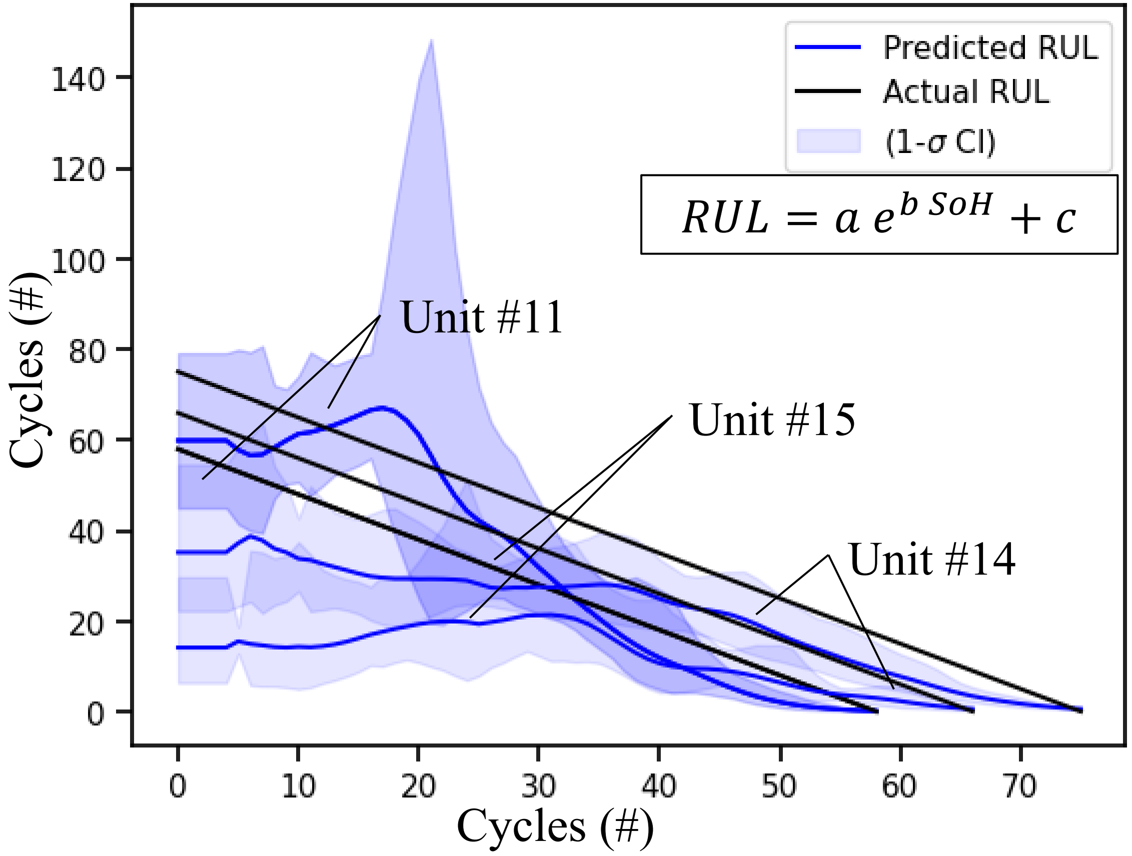


Data Preprocessing Results



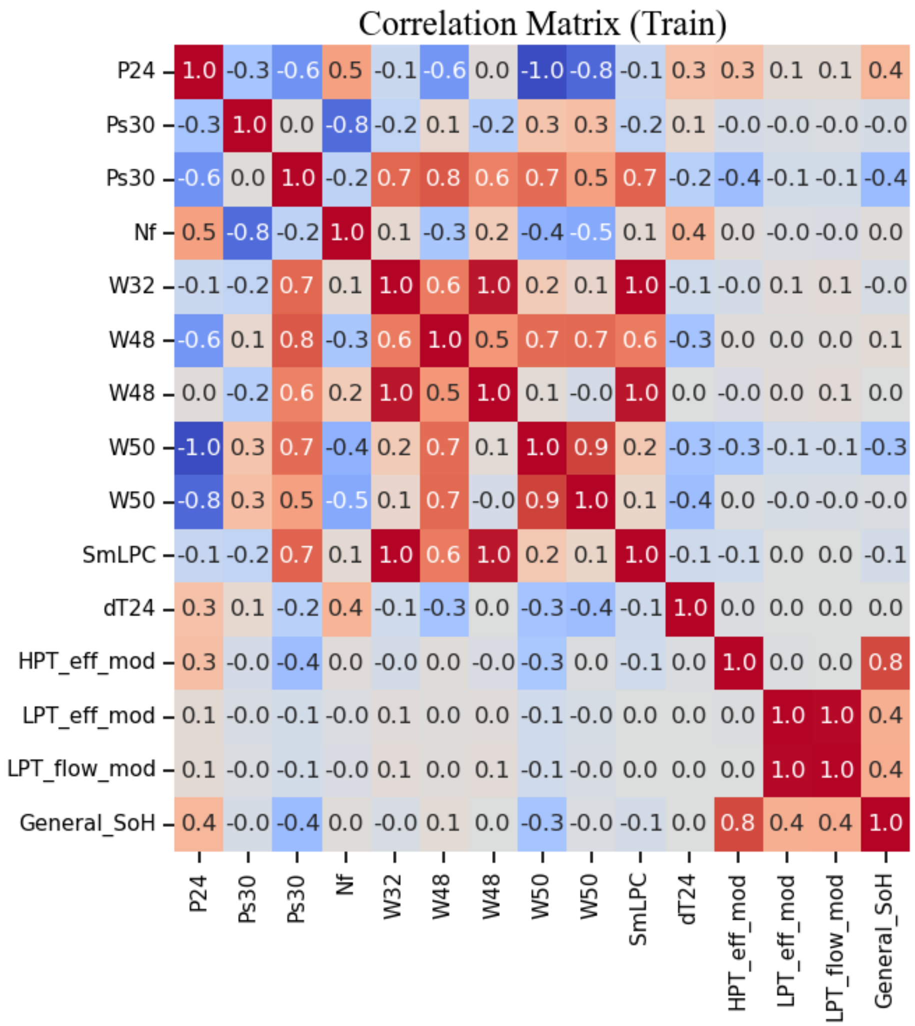
ESF-kNN Testing Results

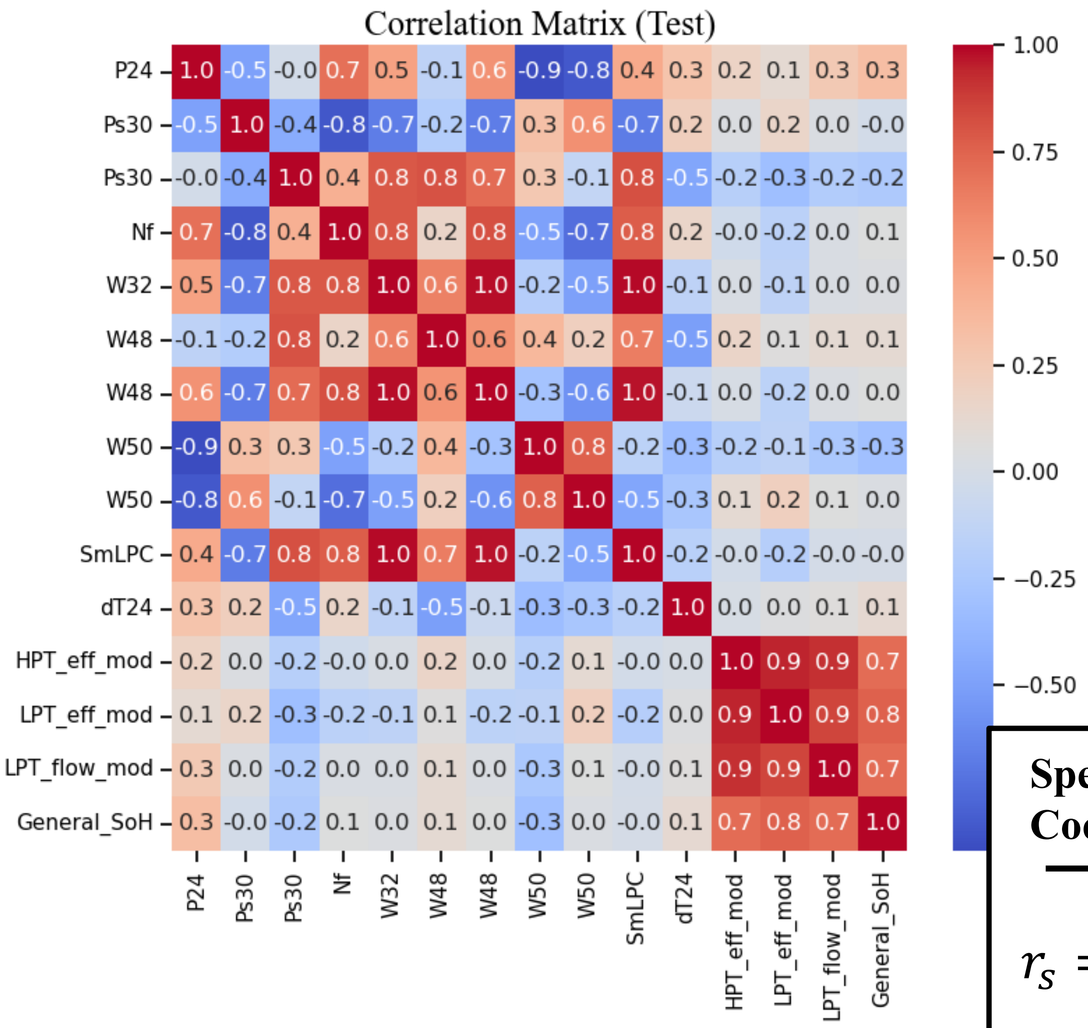




Unit (#)	SoH error (%)	RUL error (Cycles)
Testing Data		
#11	0.21 +/- 0.04	11.14+/12.01
#14	0.22 +/- 0.02	18.56+/-7.29
#15	0.22 +/- 0.07	20.58+/-6.27
Mean	0.21+/-4.03	16.79+/-8.52

Spearman Correlation Results Comparison





Spearman Correlation Coefficient

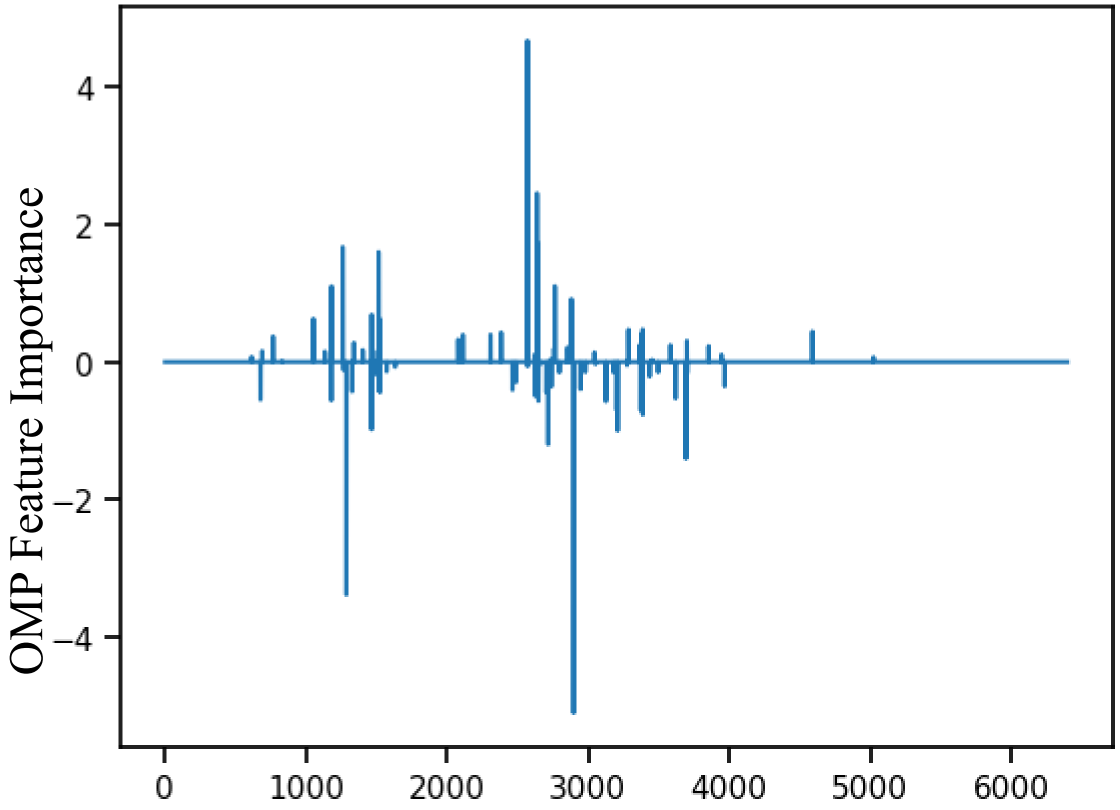
$$r_s = 1 - \frac{6\sum d^2}{n(n^2 - 1)}$$

Conclusion

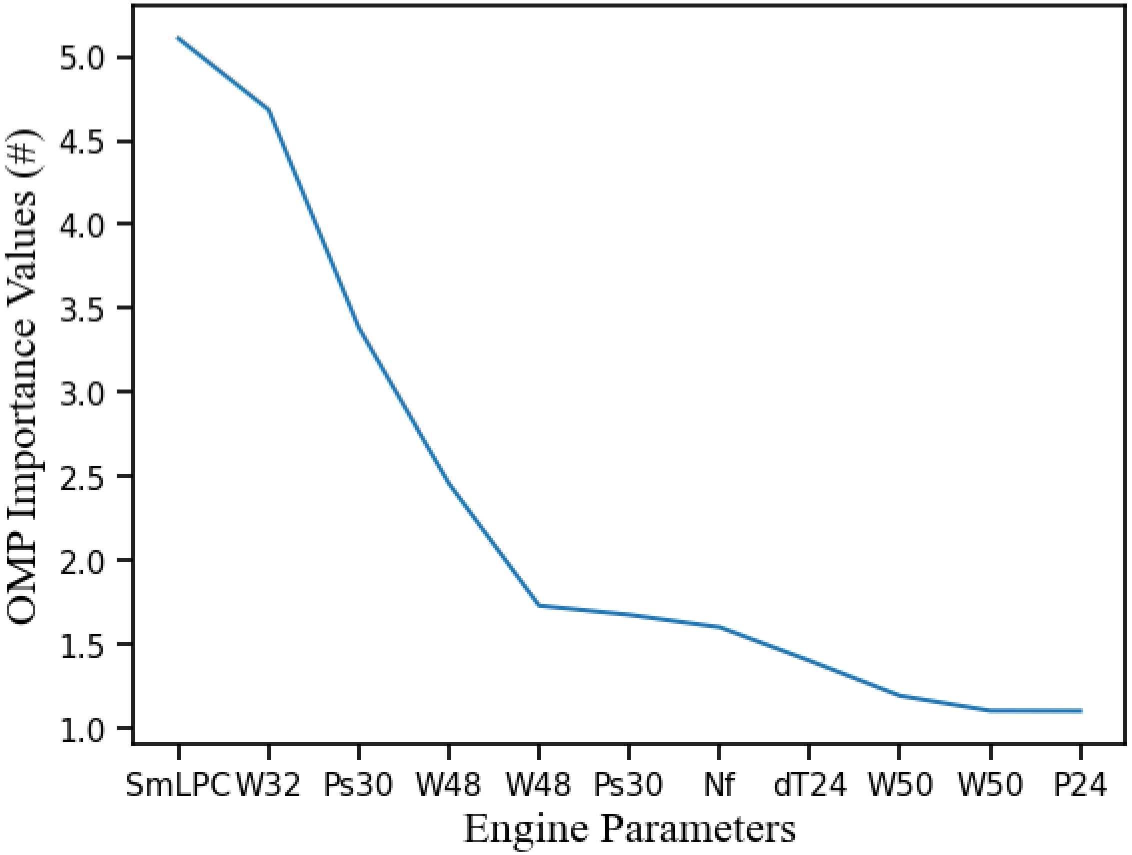
- Effectively built a predictive State of Health (SoH) estimation method for turbofan engines, incorporating advanced preprocessing and data transformation techniques.
- Created an innovative use of feature engineering, selection and state estimation called Elastic-Sparse-Functional k-NN or (ESF-kNN)
- The method achieved a remarkable reduction in feature space complexity from 6200 critical variables to just 9 (0.145%), while maintained moderate levels of predictive accuracy while greatly increasing interpretability.
- This method can aid in root cause analysis, refining data collection techniques and undertaking big data analysis.

Extra Slides

OMP Information Results



Discrete Features
(32 parameters x100 flight domain points = 6200 features)



Engine Parameters

Index	Symbol	Description	Units
1	Nf	Physical fan speed	rpm
2	Nc	Physical core speed	rpm
3	epr	Engine pressure ratio (P50/P2)	--
4	P21	Total pressure at fan outlet	psia
5	T21	Total temperature at fan outlet	°R
6	P24	Total pressure at LPC outlet	psia
7	T24	Total temperature at LPC outlet	°R
8	P30	Total pressure at HPC outlet	psia
9	T30	Total temperature at HPC outlet	°R
10	P40	Total pressure at burner outlet	psia
11	T40	Total temperature at burner outlet	°R
12	P45	Total pressure at HPT outlet	psia
13	T48	Total temperature at HPT outlet	°R
14	P50	Total pressure at LPT outlet	psia
15	T50	Total temperature at LPT outlet	°R
16	W21	Fan flow	pps
17	Fn	Net thrust	lbf
18	Fg	Gross thrust	lbf
19	SmFan	Fan stall margin	--
20	SmLPC	LPC stall margin	--
21	SmHPC	HPC stall margin	--
22	NRf	Corrected fan speed	rpm
23	NRc	Corrected core speed	rpm
24	P15	Total pressure in bypass-duct	psia
25	PCNfR	Percent corrected fan speed	pct
26	Ps30	Static pressure at HPC outlet	psia
27	phi	Ratio of fuel flow to Ps30	pps/psi

Symbol	Description	Units
accel_in	Accel limiter input	rpm/s
accel_out	Accel limiter output	rpm/s
BPR	Bypass ratio	---
DD	Decel limiter output	rpm/s
farB	Burner fuel-air ratio	---
far_HPT	HPT fuel-air ratio	---
far_LPT	LPT fuel-air ratio	---
Fdrag	Drag force	lbf
htBleed	Bleed enthalpy	
Nf_dot	Fan acceleration	rpm/s
Nc_dot	Core acceleration	rpm/s
Nf_dmd	Demanded fan speed	rpm
P2	Pressure at fan inlet	psia
PCNfRdmd	Demanded corrected fan speed	pct
PCNfR_filtered	Output of pcnfr filter for gain scheduling	pct
PR_HPC	Pressure ratio of HPC	---
PR_HPT	Pressure ratio of HPT	---
PR_LPT	Pressure ratio of LPT	---
tau_HPC	Torque of HPC	ft-lb
tau_HPT	Torque of HPT	ft-lb
tau_LPT	Torque of LPT	ft-lb
TRA	Throttle resolver angle	deg
T2	Total temperature at fan inlet	°R
W22	Flow out of LPC	lbm/s
W25	Flow into HPC	lbm/s
W31	HPT coolant bleed	lbm/s
W32	HPT coolant bleed	lbm/s
W48	Flow out of HPT	lbm/s
W50	Flow out of LPT	lbm/s
Wf_dot	Derivative of fuel flow	lbm/s^2
x1,…,x5	Solver outputs	