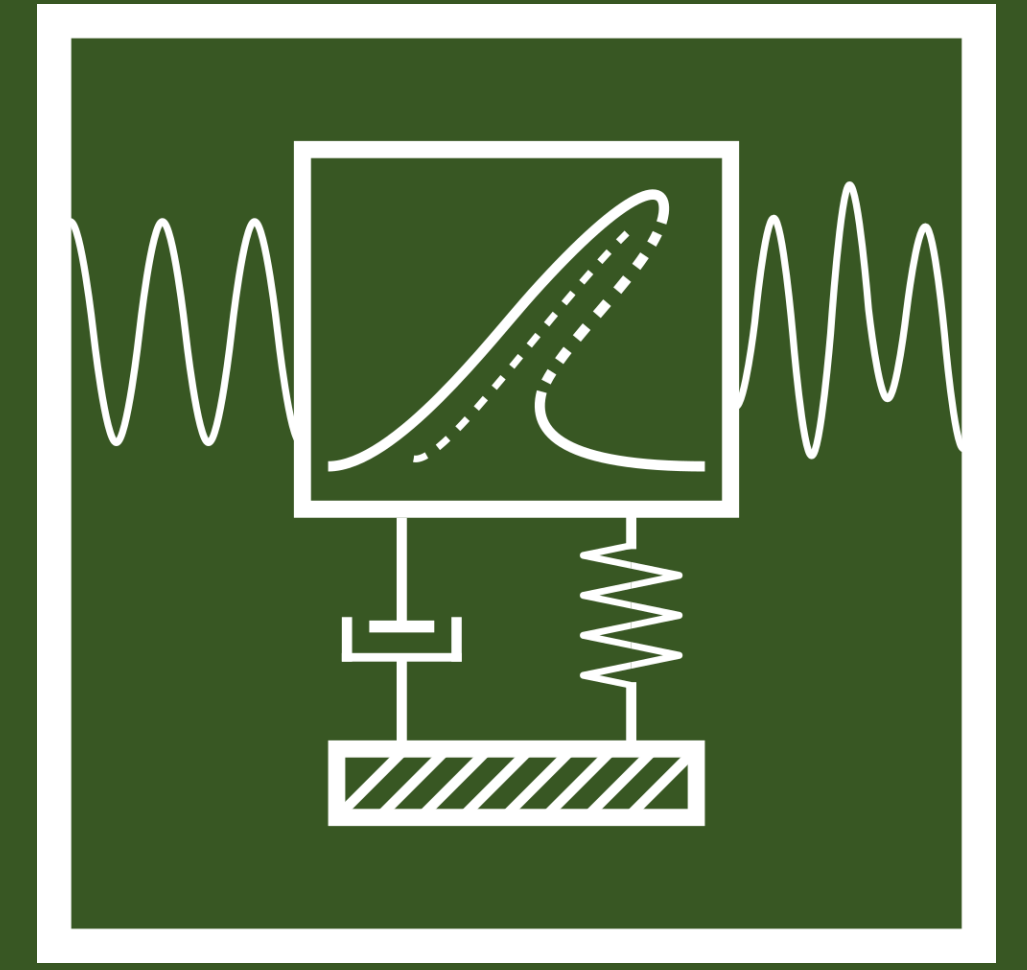


Color Recurrence Plots from Uniform Delay Embeddings for Bearing Degradation Prognostics

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A Abstract

Vibration-based prognostics require features that track degradation and are computationally inexpensive enough for on-line use. Recurrence analysis offers such features, but reconstructing the bearing's attractor with individually chosen (non-uniform) delays turns parameter selection into a combinatorial search. We show on the IMS run-to-failure dataset that the best uniform delay vector performs almost as well as the globally best non-uniform one, collapsing the search from 50^4 candidates to 50. From this embedding, we build color recurrence plots and use six simple statistics of these plots to predict remaining useful life more accurately than standard binary recurrence plots allow.

01 Methods

Data. IMS bearing dataset (NASA): four bearings on one shaft, 2000 RPM, 6000 lbs. One file per 10 min until failure, each 1 s of raw unfiltered vibration (20 480 samples at 20 kHz).

Embedding. Dimension $d = 5$, delays $\tau \in \{1 \dots 50\}$, maximizing the separation of the reconstructed state vectors. All $50^4 = 6\,250\,000$ non-uniform vectors searched exhaustively, against the 50 uniform ones.

Color recurrence plot. The 10 composite delays give 10 binary shares, each thresholded for equal black and white pixel counts; their sum is the plot C (142×142 pixels, 11 color levels). Thresholds are fixed once on healthy data, so later changes reflect bearing dynamics alone.

Features and regression. Six statistics of C, and of the binary plot R: mean, median, SD, skewness, kurtosis, entropy. RUL from XGBoost, Random Forest and Gradient Boosting; 80/20 split, 21 runs, lasted 72 h.

02 Results

Hypothesis confirmed. Defective channel CH3: the best uniform vector (49, 49, 49, 49) is the global optimum. Healthy channel CH4: it ranks 29 391st of 6.25 million, yet lies only 0.18 % below the global best.

Binary plots darken but do not order themselves. Textures differ between high and low RUL, but within each group they vary erratically.

Color recurrence plots evolve smoothly. Faint diagonals emerge as RUL falls and intensity drifts monotonically, because averaging over 10 projections cancels local pattern noise.

Accuracy (last 72 h, CH3): color recurrence plots with Random Forest reach $r^2 = 0.935$, MAE = 3.47 h, versus $r^2 = 0.816$ and MAE = 5.97 h for binary plots with Gradient Boosting. No overfitting; accuracy is highest at low RUL, where it matters most.

Healthy channels work too. CH1, CH2 and CH4 give comparable accuracy. All four bearings share one shaft, and the defect leaks into every measurement.

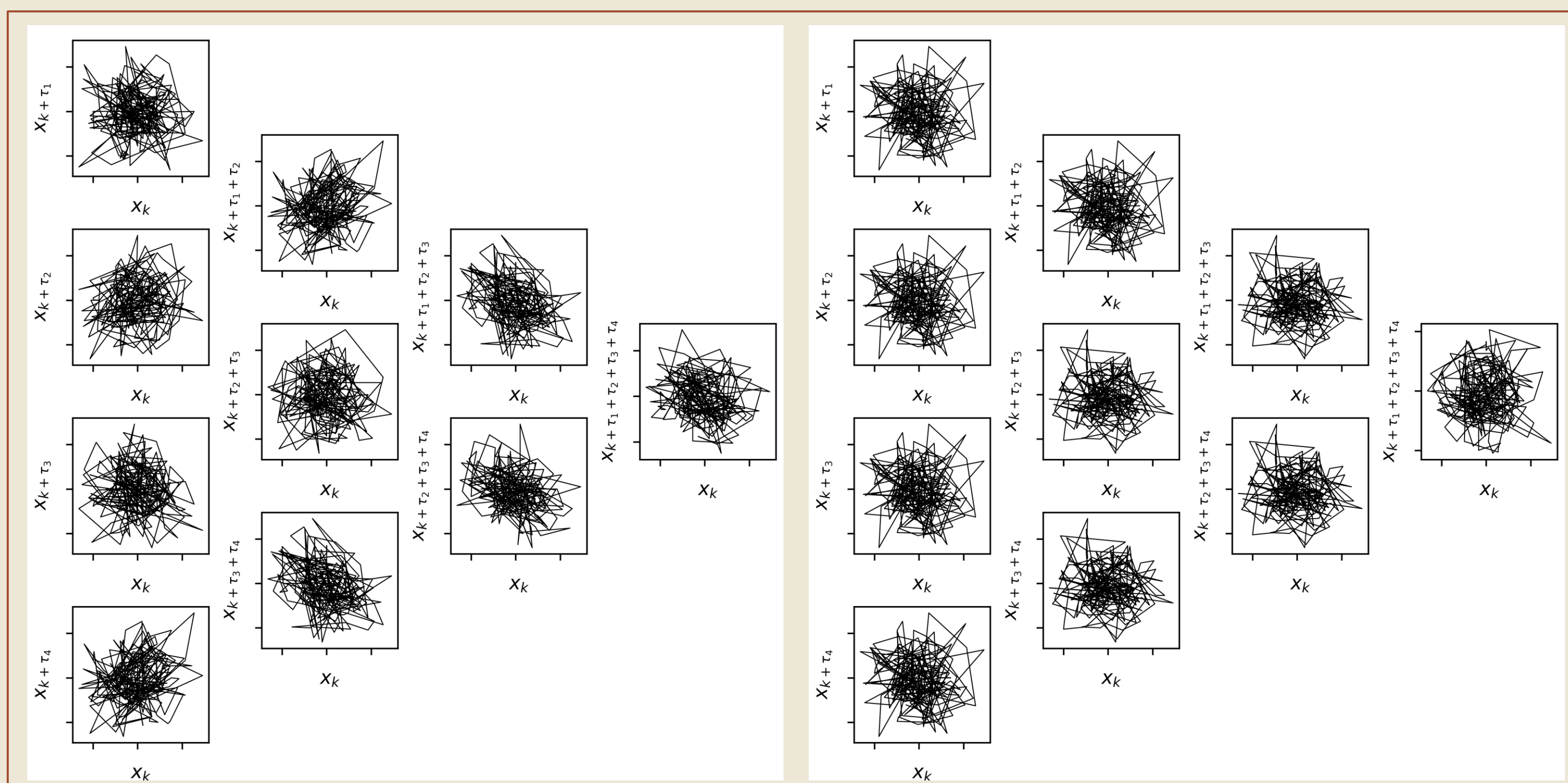


Fig 1. Construction of the color recurrence plot: ten dichotomous digital shares from the composite delays of global best delay vector (22,25,21,47) (left) and the uniform vector (49, 49, 49, 49) (right), averaged into a single 142×142 plot with 11 intensity levels.

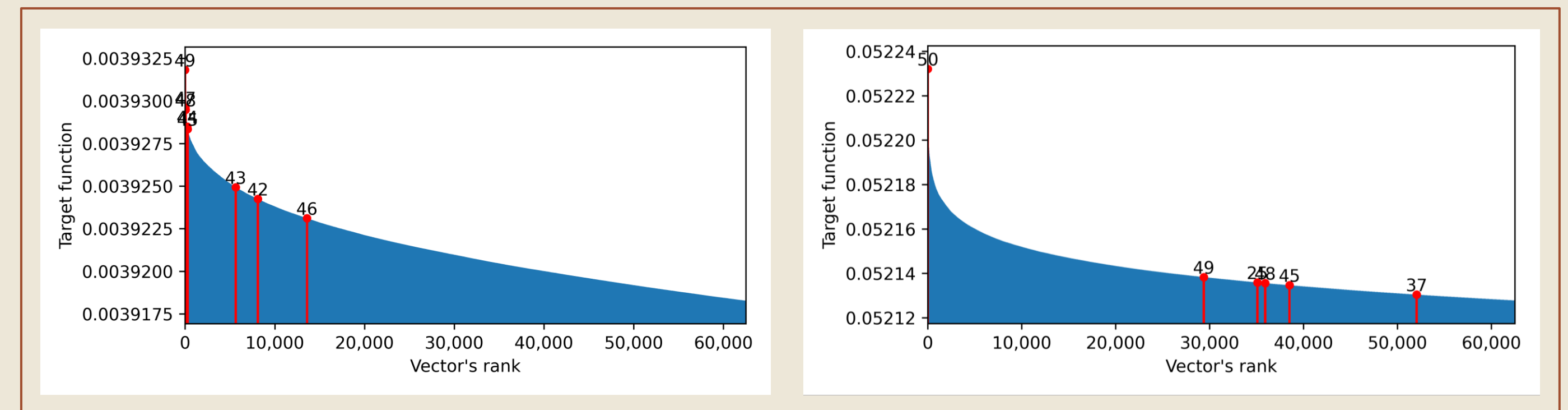


Fig 2. Top 1 % of target function values F over 6 250 000 non-uniform delay vectors, sorted. Red lines mark uniform vectors; numbers give the delay. (left) CH3, RUL = 0: the best uniform vector is the global optimum. (right) CH4, healthy: within 0.18 % of it.

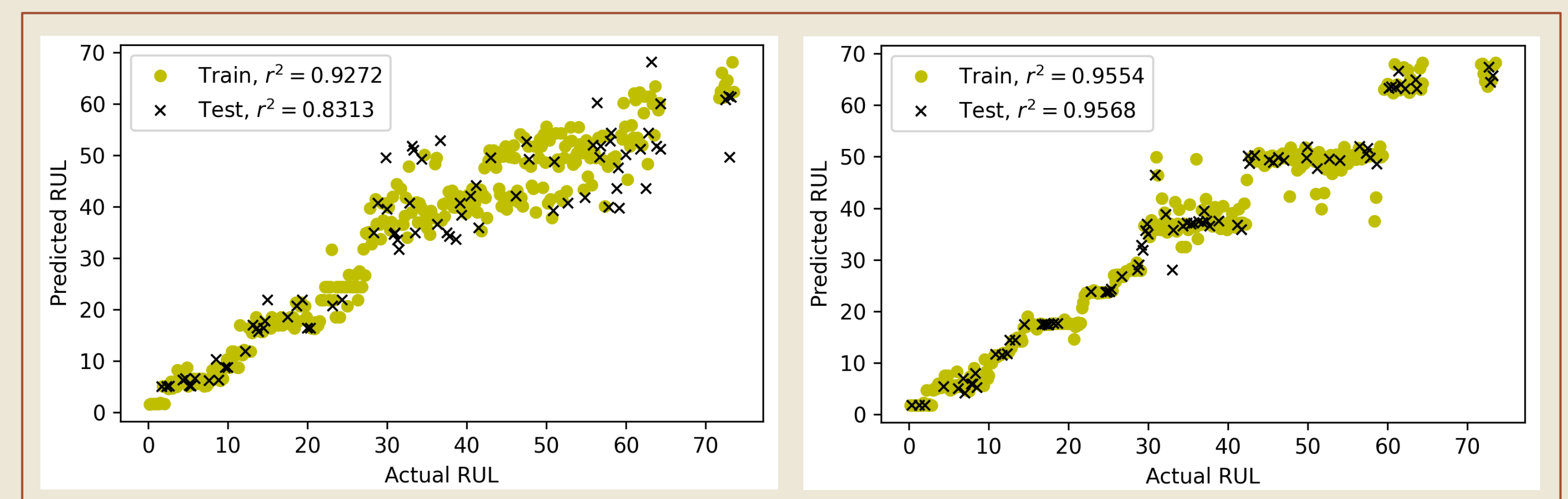


Fig 3. RUL prediction from CH3, last 72 h binary recurrence plots, GBR: $r^2 = 0.816$, MAE = 5.97 h. (left) color recurrence plots, RFR: $r^2 = 0.935$, MAE = 3.47 h (right).

03 Discussion

The target function decays exponentially from its maximum, so its top is a broad plateau and a uniform vector lands on it. Non-uniform flexibility buys little, at five orders of magnitude in search effort.

A binary plot answers one fragile question per pixel pair: recurrent or not. Summing ten thresholded shares turns that into a graded intensity: local noise cancels, the global trend survives. Recurrence features stay flat for most of the bearing's life and move only in the final 24–72 h. Hence the operating mode: monitor continuously, switch on RUL estimation once degradation accelerates.

04 Conclusions

1. The best uniform delay vector performs on par with the globally optimal non-uniform vector for bearing vibration: confirmed by exhaustive search.
2. Embedding parameter selection reduces to a sweep over one integer, making recurrence-based reconstruction viable for on-line use.
3. Color recurrence plots outperform standard binary plots as prognostic features: r^2 0.93 vs 0.82, MAE 3.47 h vs 5.97 h.
4. The averaging step gives implicit noise robustness, with no filtering of the raw signal anywhere in the pipeline.

References

- [1] J.-P. Eckmann, S. O. Kamphorst, and D. Ruelle, "Recurrence plots of dynamical systems," *Europhysics Letters*, vol. 4, no. 9, pp. 973–977, 1987, <https://doi.org/10.1209/0295-5075/4/9/004>
- [2] V. Petrauskienė, M. Pal, M. Cao, J. Wang, and M. Ragulskis, "Color recurrence plots for bearing fault diagnosis," *Sensors*, vol. 22, no. 22, 8870, 2022, <https://doi.org/10.3390/s22228870>
- [3] J. Lee, H. Qiu, G. Yu, and J. Lin, "Bearing data set," IMS, University of Cincinnati, NASA Prognostics Data Repository, NASA Ames Research Center, Moffett Field, CA, 2007.