Online damage detection using topological data analysis

UNIVERSITY OF South Carolina
College of Engineering and Computing

Daniel Coble and Austin R.J. Downey

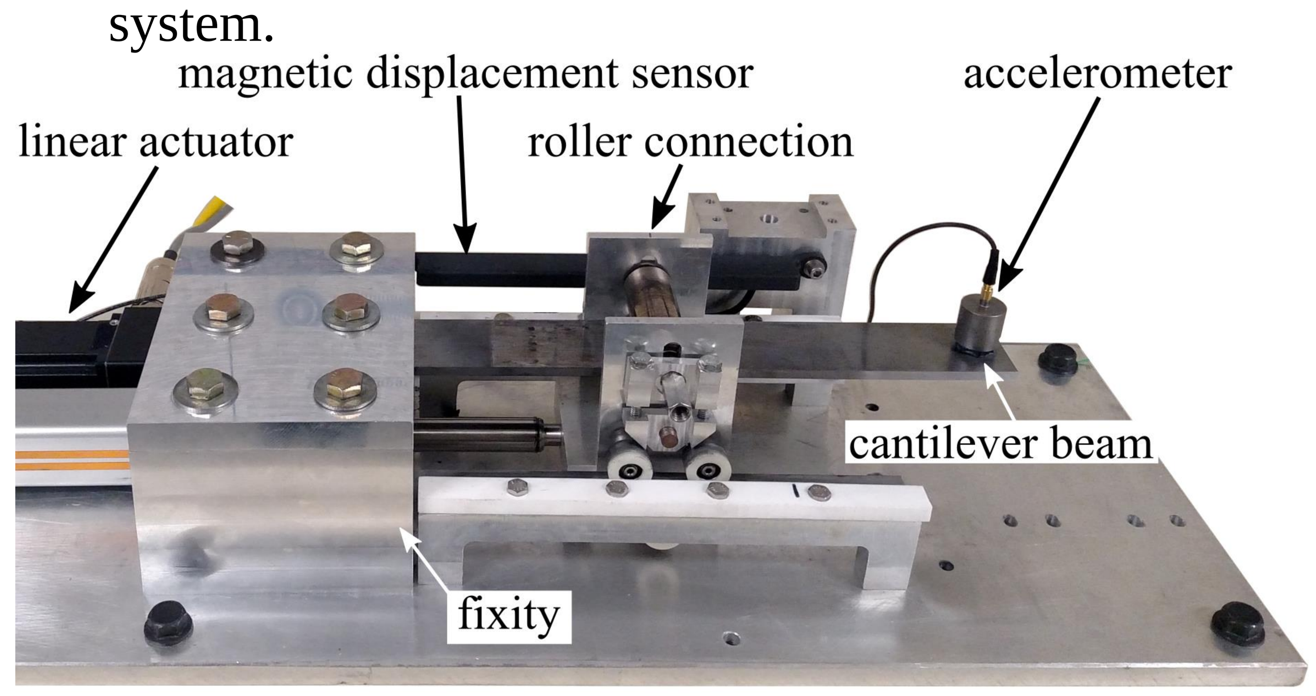
ARTS-Lab
Adaptive Real-Time Systems Laboratory

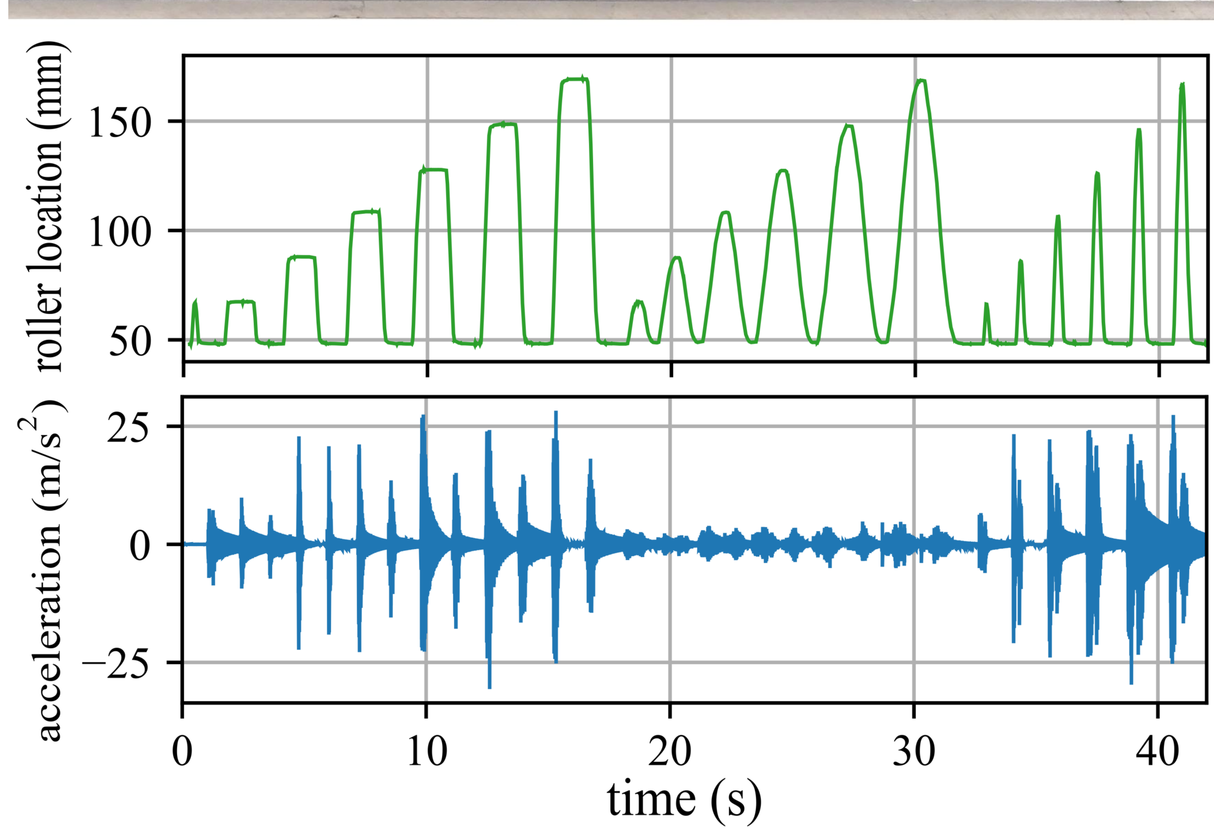
Introduction

- High-rate dynamics consists of structures subjected to impact loading that results in accelerations greater than 100 g during time periods of less than 100 milliseconds.
- An important research objective is to create data-driven models capable of producing state prediction from a time-domain signal.

DROPBEAR Testbed

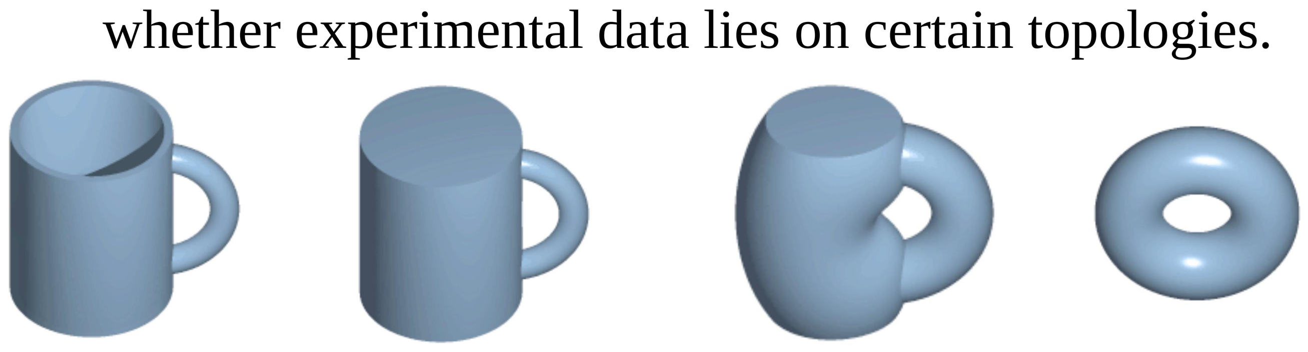
- The DROPBEAR testbed consists of cantilever beam with a controllable roller to alter "state" of the system.





Topological data analysis

- Topology is the study of geometric constants which persist under deformation.
- Topological data analysis attempts to ascertain whether experimental data lies on certain topologies.



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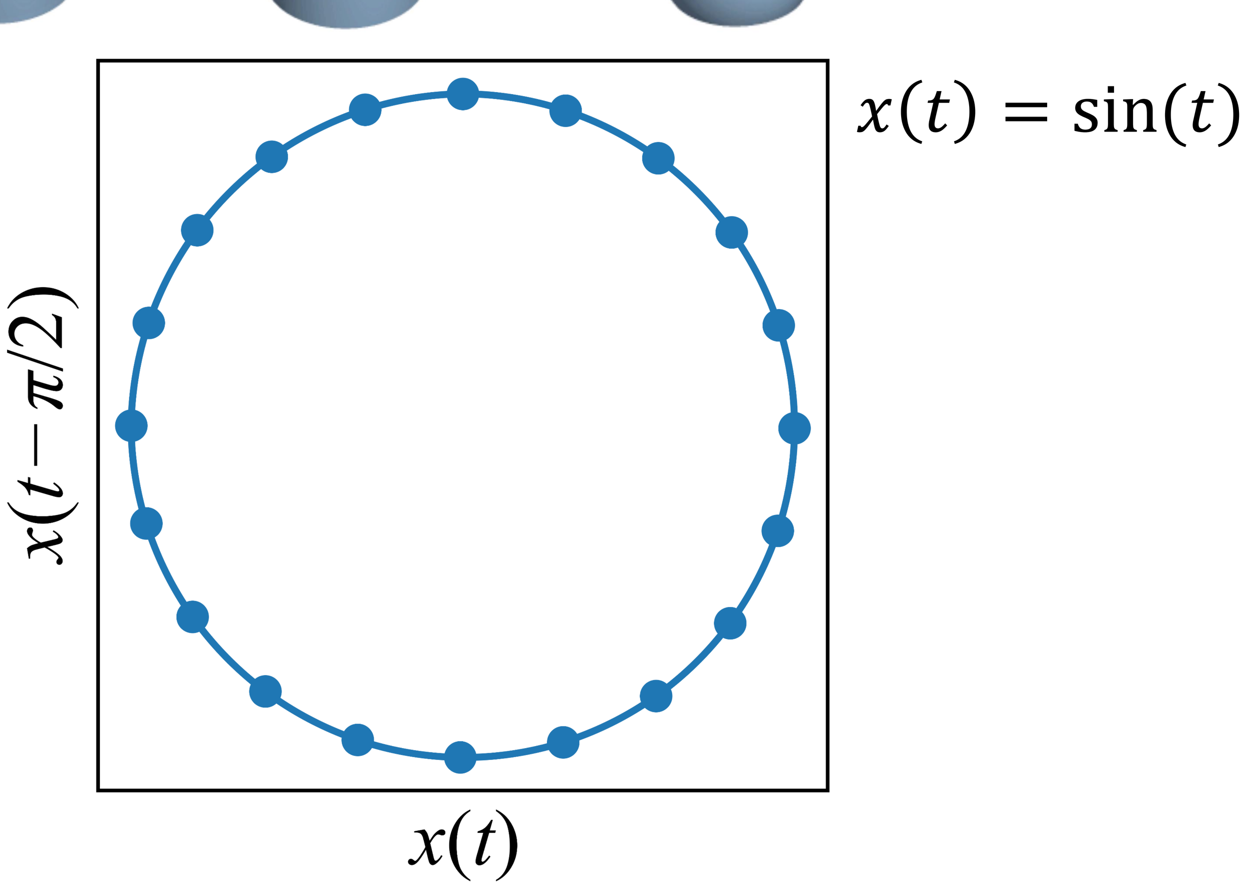


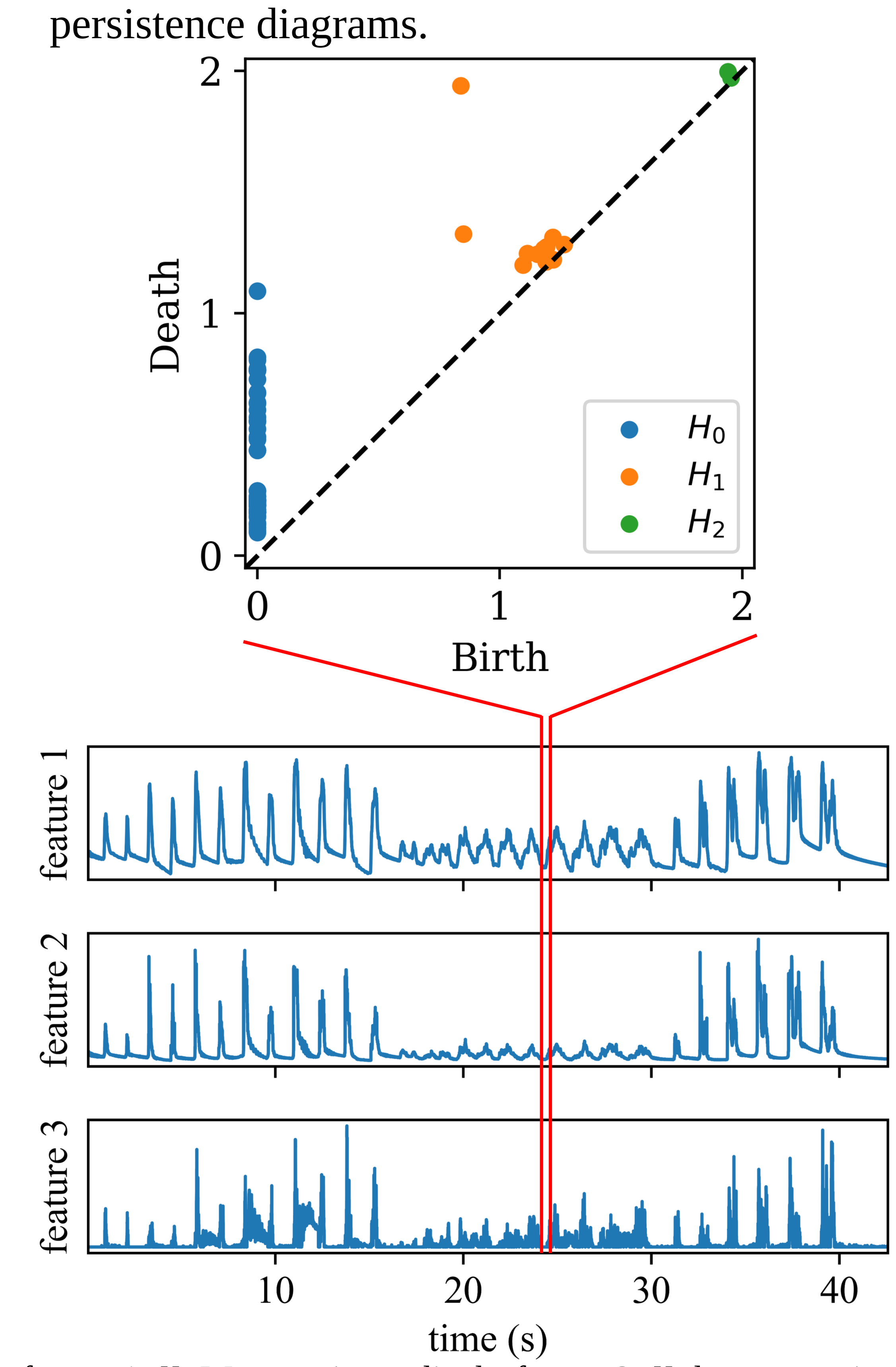
Methods

Feature extraction

- The acceleration signal was windowed into sections of 0.05 s and embedded using the Takens' embedding.

$$y(t) = [x(t), x(t+\tau), x(t+2\tau), \dots, x(t+(d-1)\tau)]$$

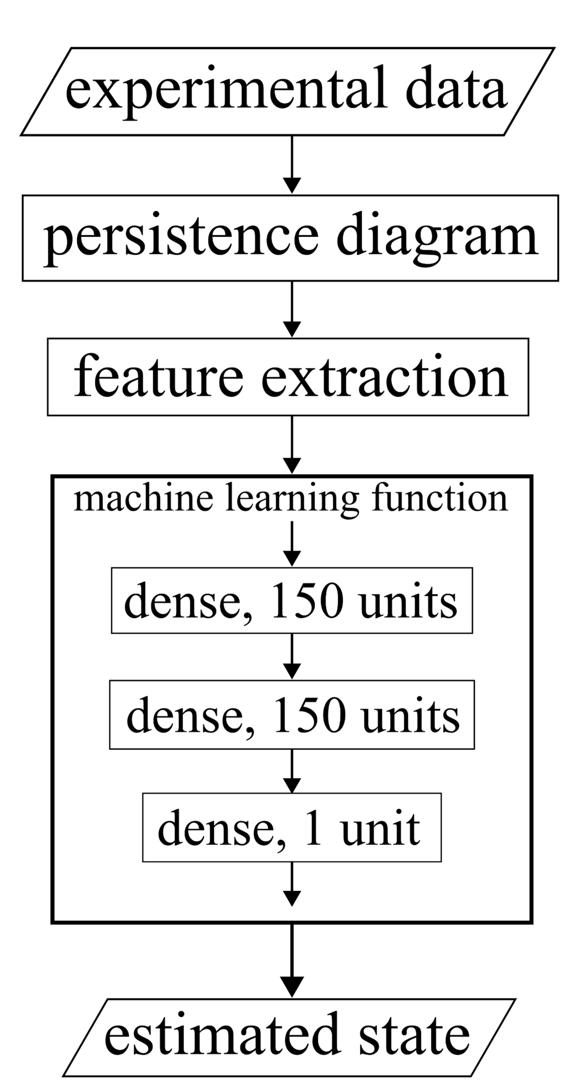
- Our analysis found an imbedding dimension of $d = 6$ to be optimal.
- 29 topological features were extracted from persistence diagrams.



feature 1: H_0 Wasserstein amplitude. feature 2: H_1 longest persistence birth. feature 3: H_2 Betti number.

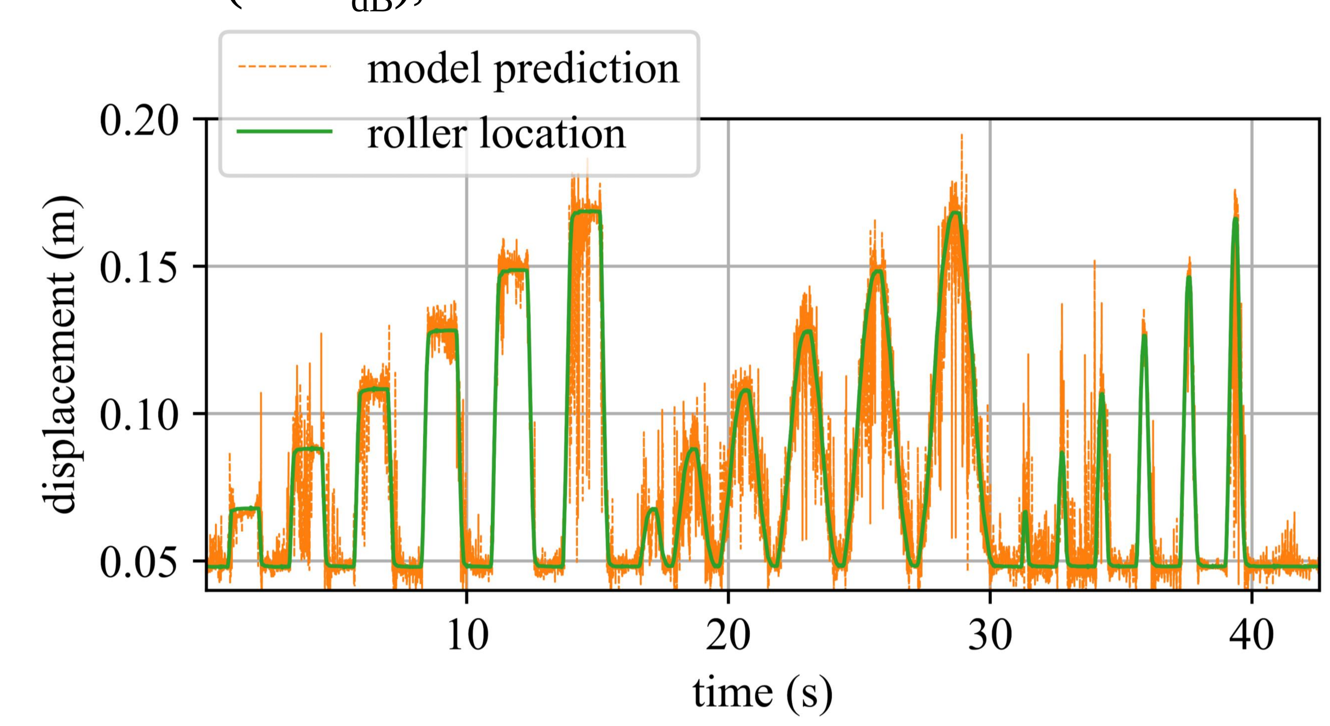
Machine learning

- A machine learning function correlates the extracted topological features to roller location.
- Feature importance is heuristically measured using its gradient.

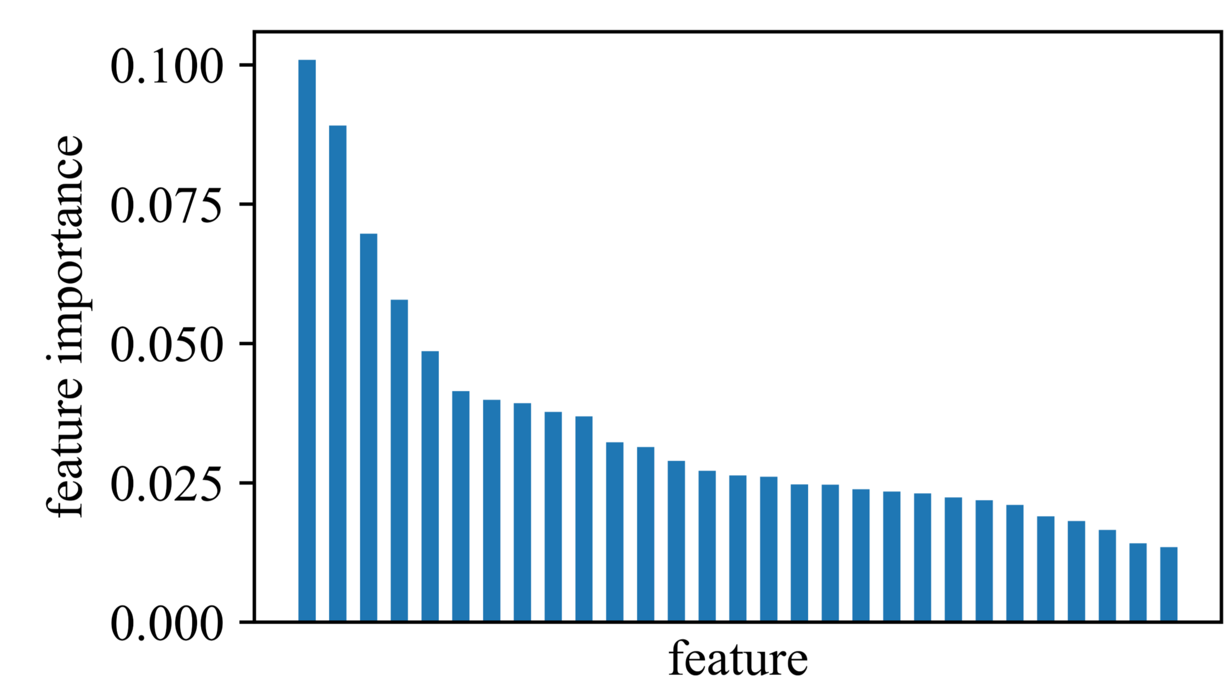


Results

- Performance was examined using signal-to-noise ratio (SNR_{dB}), RMSE.



- Model demonstrated SNR of 18.6 dB and RMSE of 10.1 mm.



- Gradient analysis identified H_0 Wasserstein amplitude, H_1 first birth, and H_2 Betti number as the three most important features.

Conclusion

- TDA/ML methods achieved comparable accuracy to previously investigated pure-ML methods [2].
- ML allowed an investigation into feature importance.
- Future work will focus on improving computation speed under high-rate dynamical constraints.

References

[1]https://commons.wikimedia.org/wiki/File:Mug_and_Torus_morph.gif

[2] Towards online structural state-estimation with sub-millisecond latency. *92nd Shock and Vibration Symposium*, 2023.

[3] All code and models have been made publicly available via a GitHub repository. https://github.com/ARTS-Laboratory/Real-time-Topological-Data-Analysis