

Sub-Millisecond Construction of Digital Twin Using AI

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Introduction

High-rate systems

- Experiencing accelerations higher than $100 g_n$ in less than 1 ms
- Large uncertainties in the external loads
- High levels of non-stationarities
- Generation of unmodeled dynamics



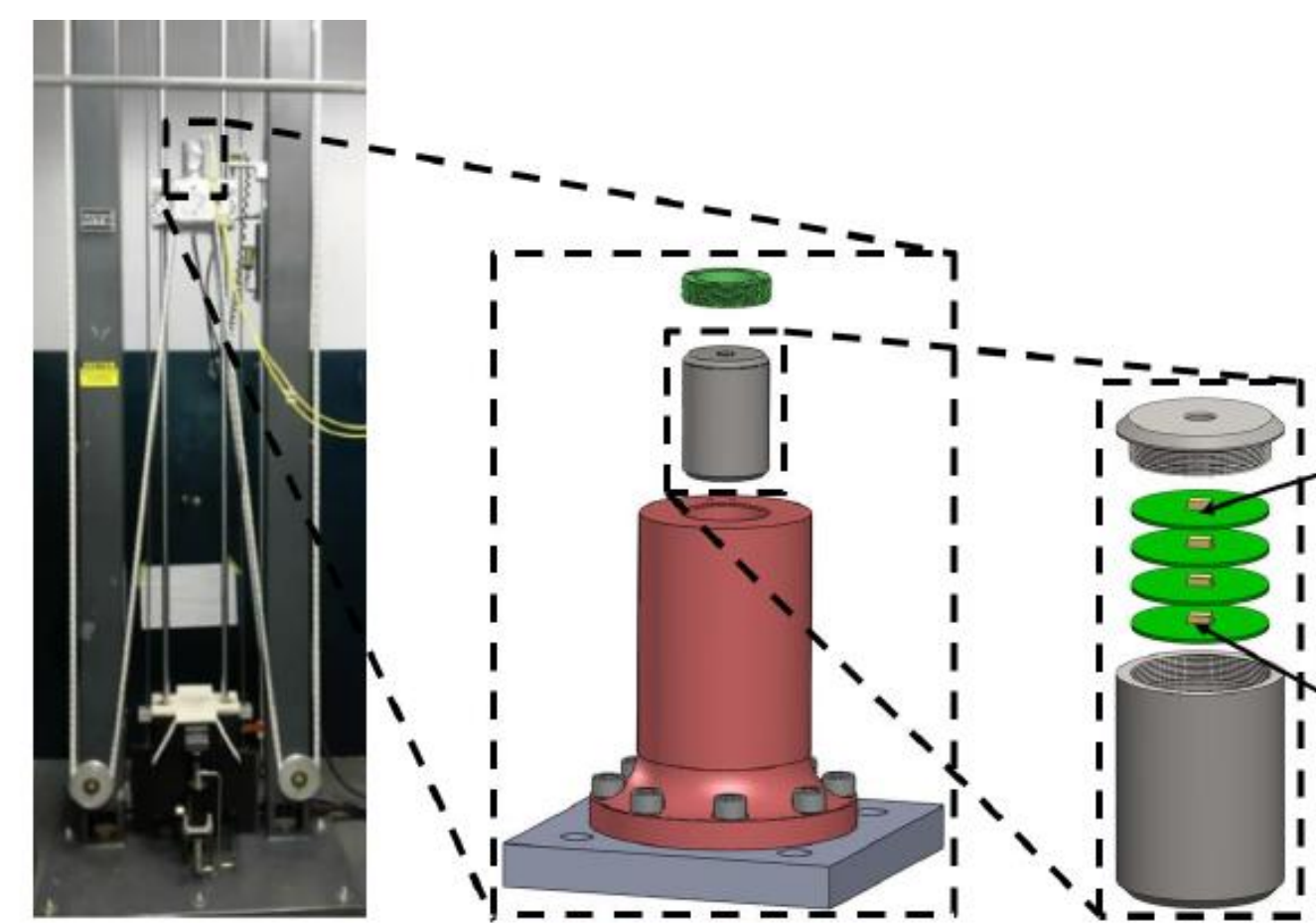
High-rate structural health monitoring challenges

- Unknown or uncertain dynamics
- Real-time modeling requirement
- Less than $100 \mu s$ computation time per decision step
- Limited access to training data

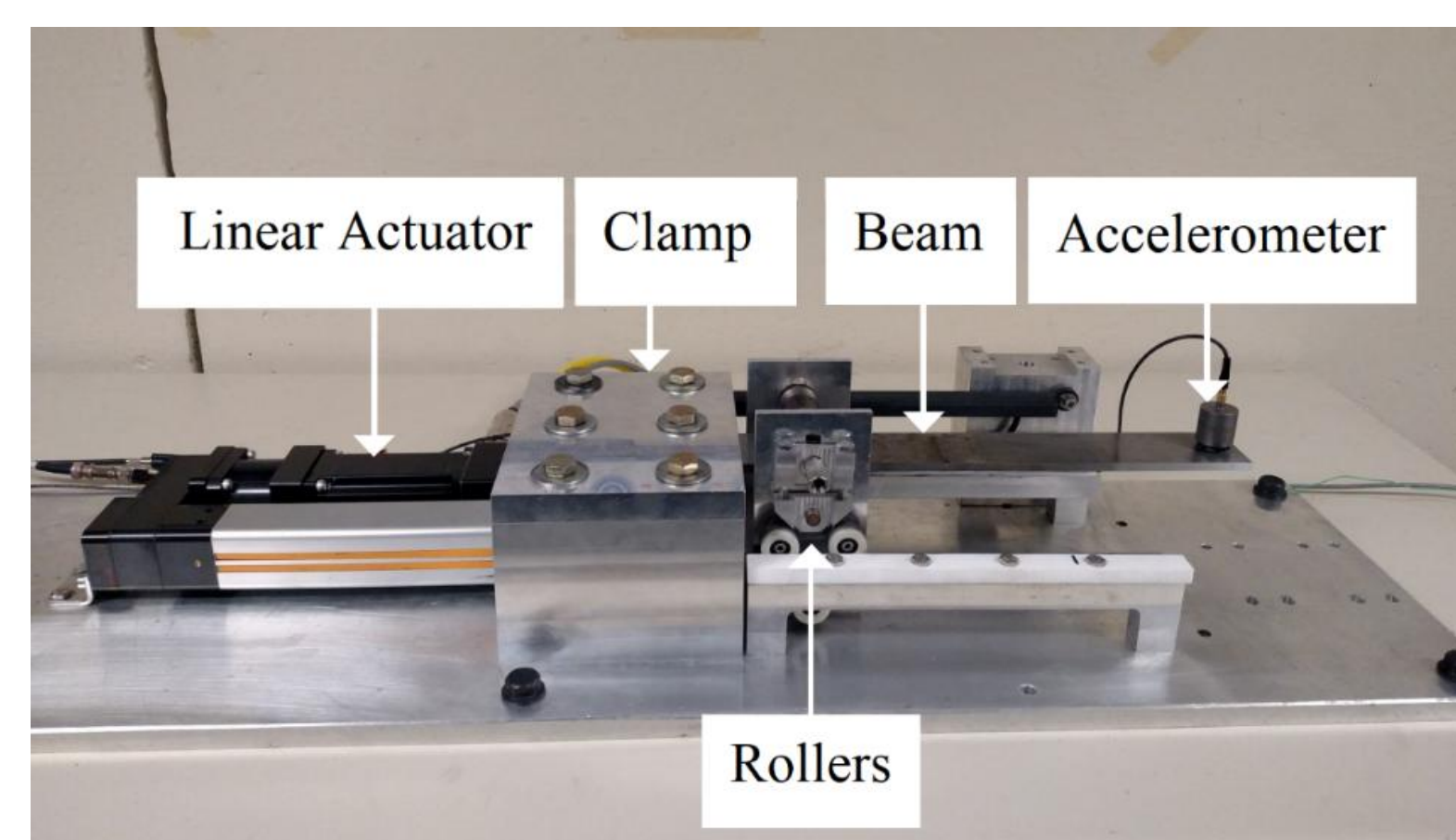


High-rate laboratory datasets

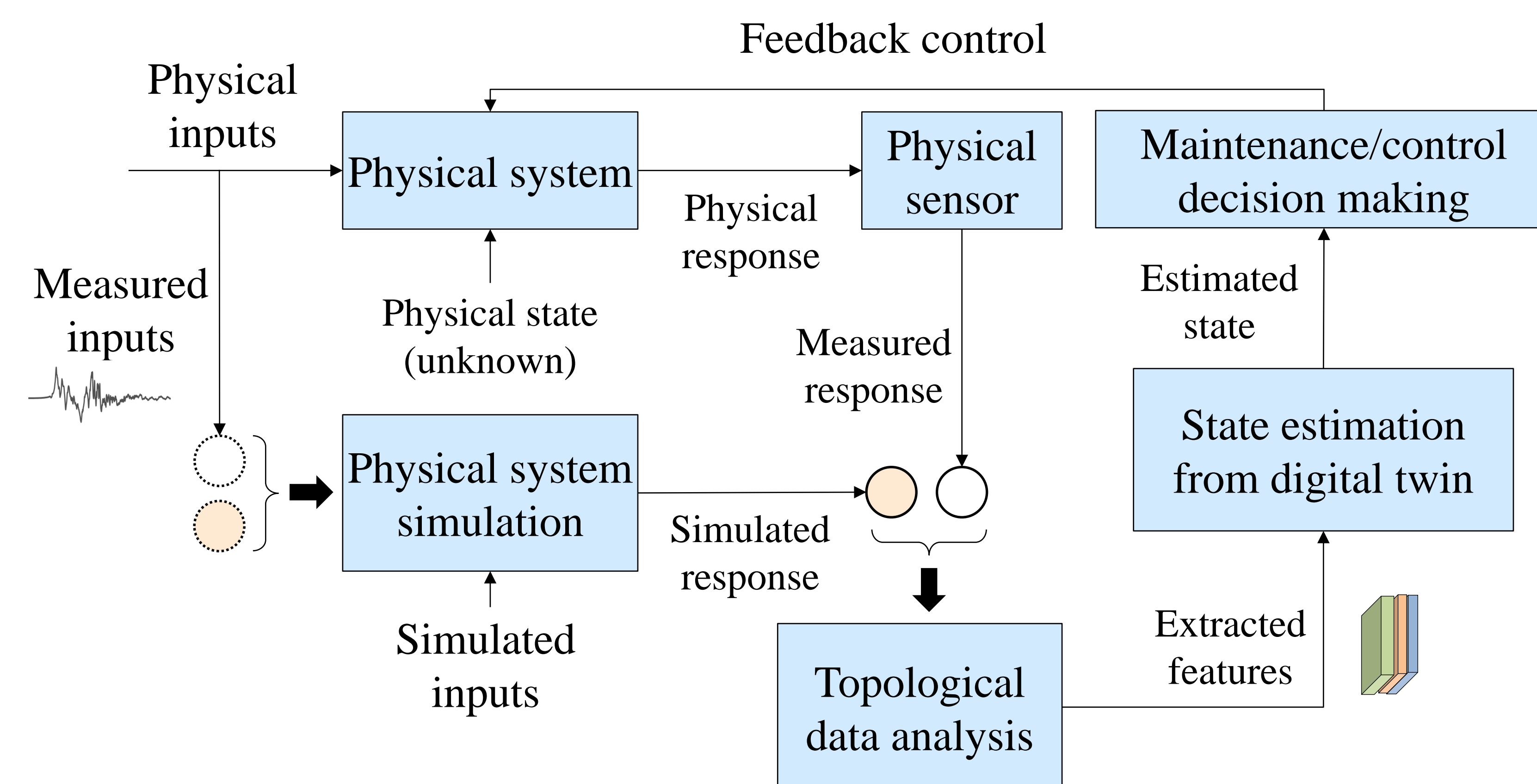
Drop tower



DROPBEAR



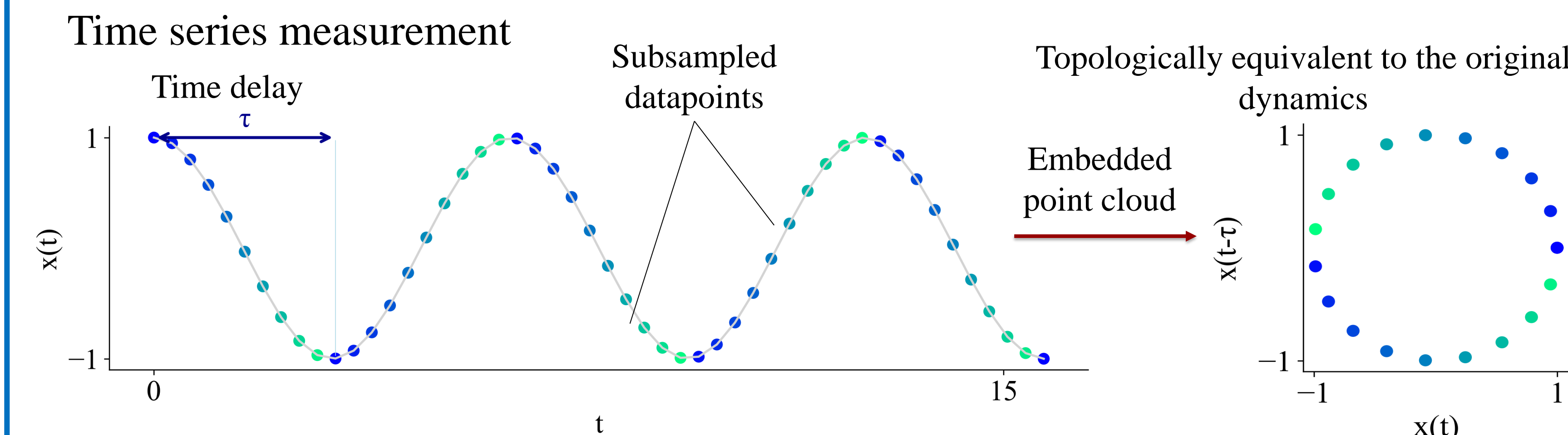
Digital twin for high-rate state estimation



Methodology

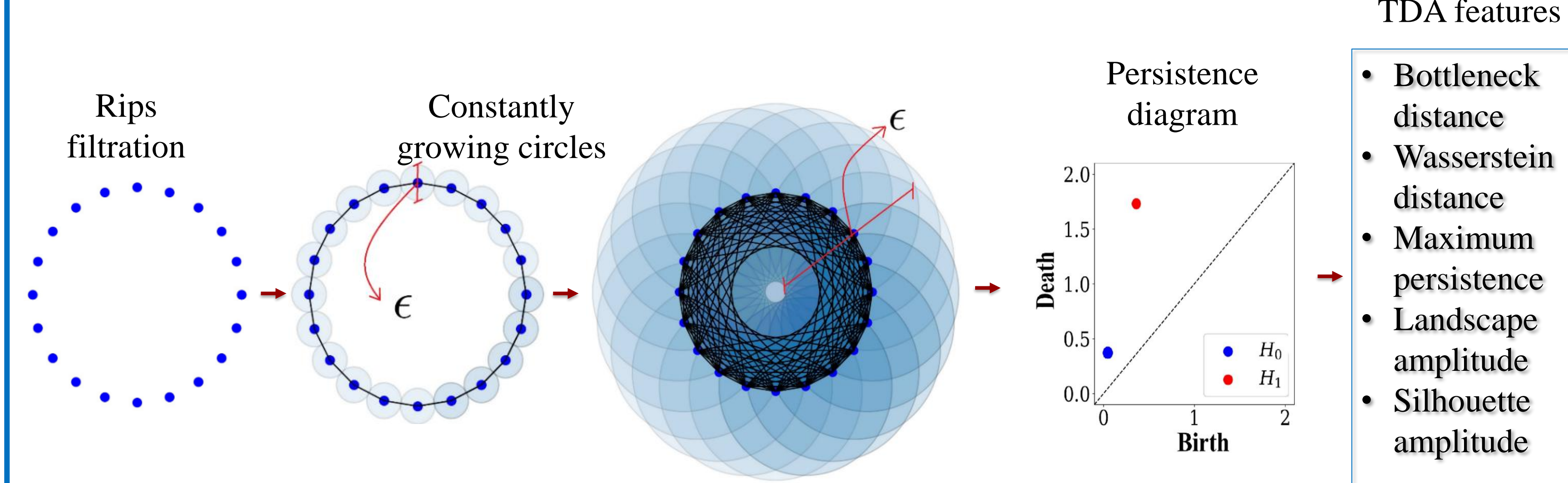
Background

Takens' embedding theorem

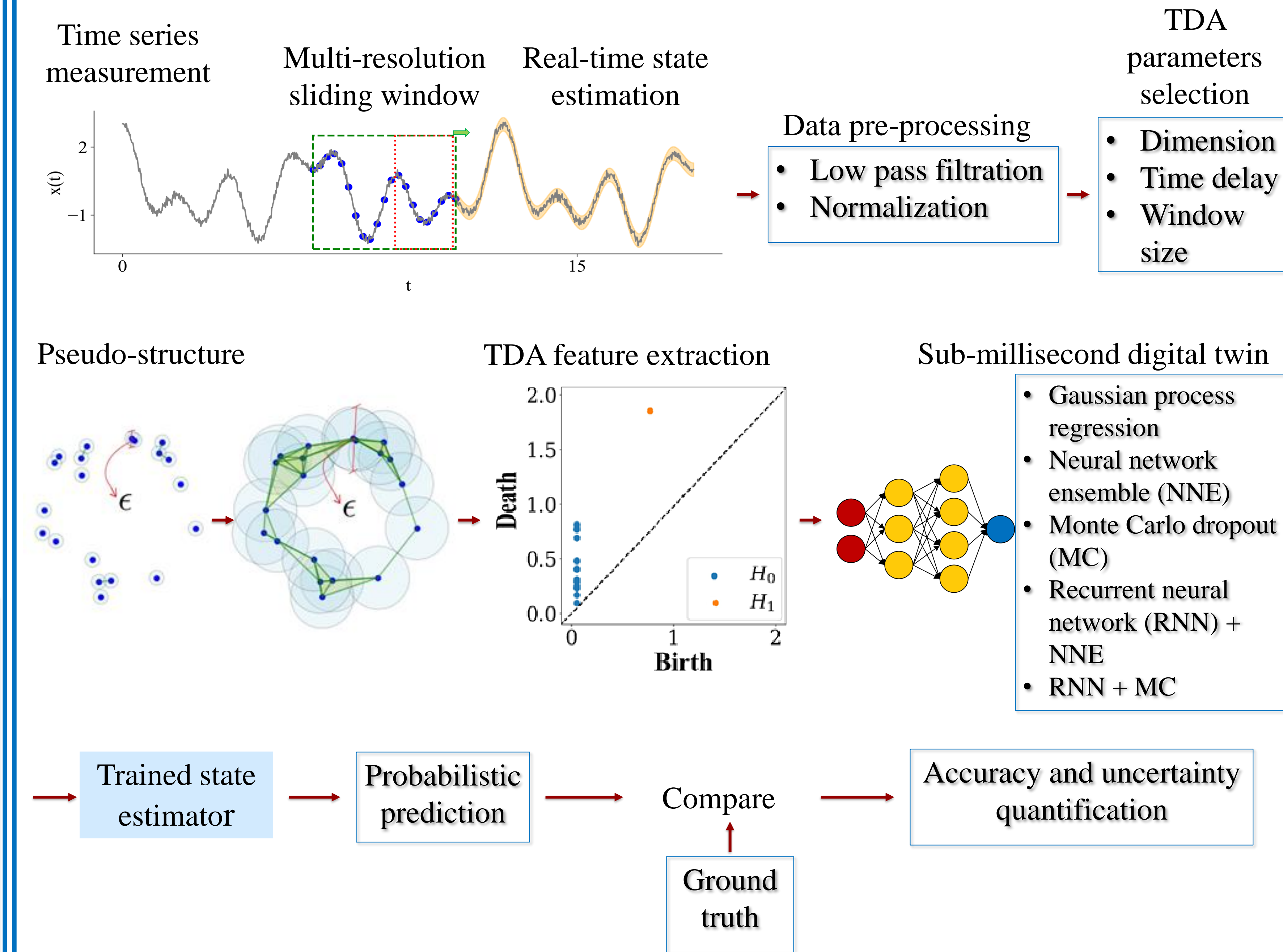


Persistent homology

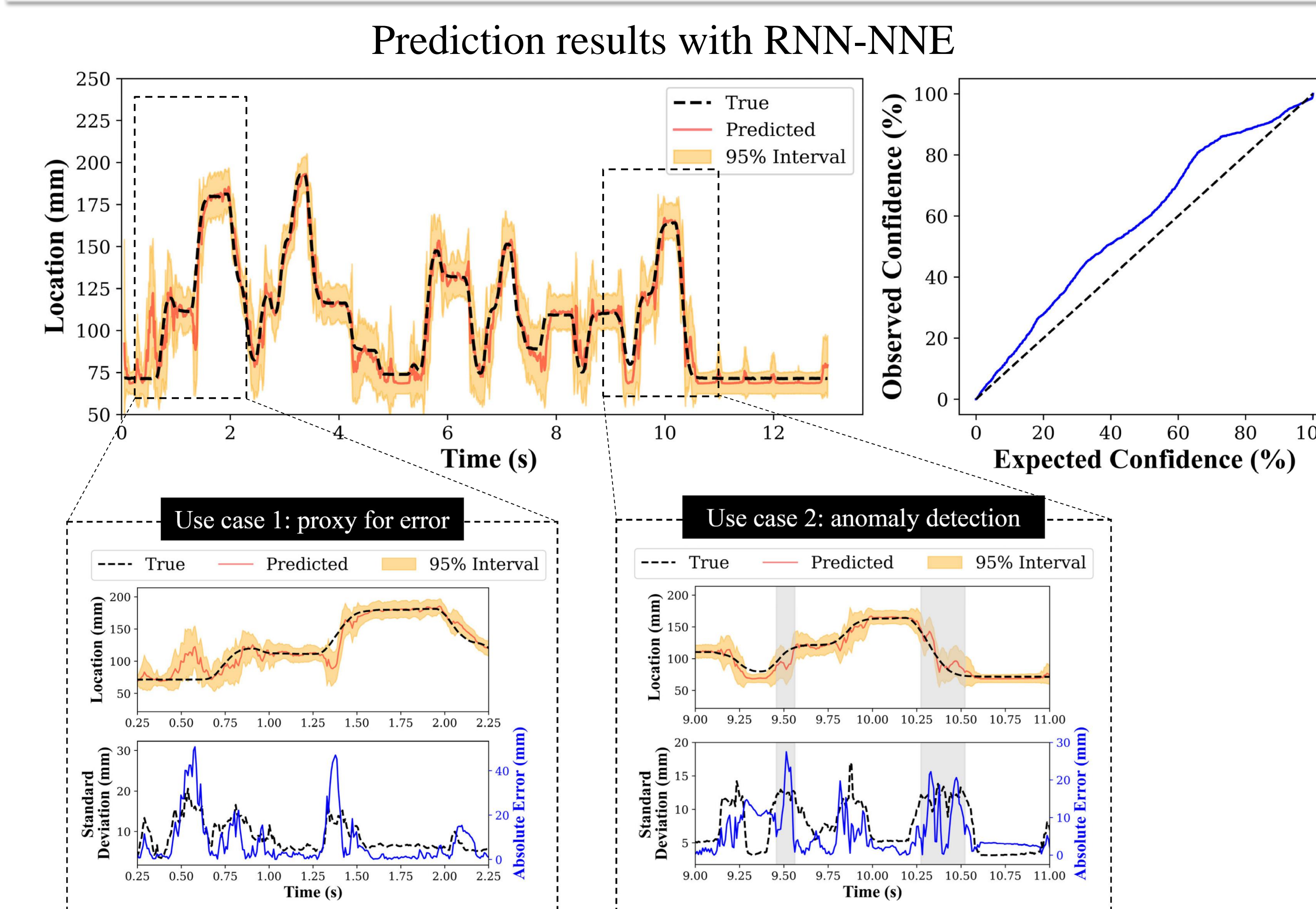
- Employing simplicial complex on embedded point cloud to compute homology groups
- Keep a record of various ϵ values
- H_0 zero-dimensional hole, H_1 one-dimensional hole



Algorithm



Results



Model performance metrics

Model	MAE (mm)	TRAC	NLL	ECE (%)	Computation time per sample (ms)
NN	6.856	0.991	-	-	26.896
RNN	5.901	0.994	-	-	26.961
GPR	6.508	0.991	-2.339	10.625	27.107
MC Dropout	8.475	0.990	3.282	22.264	26.932
NNE	6.309	0.992	-4.304	13.621	27.220
RNN-MC	7.524	0.992	-2.613	16.001	27.156
RNN-NNE	5.030	0.995	-2.498	7.817	27.158

Parameters for TDA feature extraction

Parameter	Value (unit)
H_0 Window size	0.1 (s)
H_1 Window size	0.1333 (s)
Time delay (τ)	0.0083 (s)
Embedding dimension (d)	3
Window step size	1 (step)

References

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- Chua, Yang Kang, Daniel Coble, Arman Razmarashooli, Steve Paul, Daniel A. Salazar Martinez, Chao Hu, Austin RJ Downey, and Simon Laflamme. "Probabilistic machine learning pipeline using topological descriptors for real-time state estimation of high-rate dynamic systems." Mechanical Systems and Signal Processing 227 (2025): 112319.

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