Developing High-rate digital twins for structures under shock loading

(and other content)

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Adaptive Real-time Systems Laboratory (ARTS-Lab)

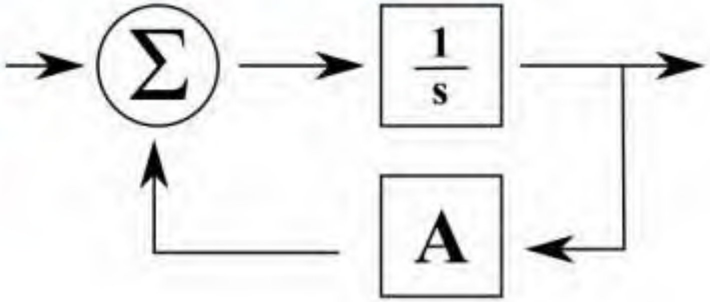
ARTS-Lab
Adaptive Real-Time Systems Laboratory

Research Interest:

1. Real-time model updating
2. Distributed and autonomous sensing
3. Real-time decision making
4. Cyber-physical systems

Research Group, Spring 2022

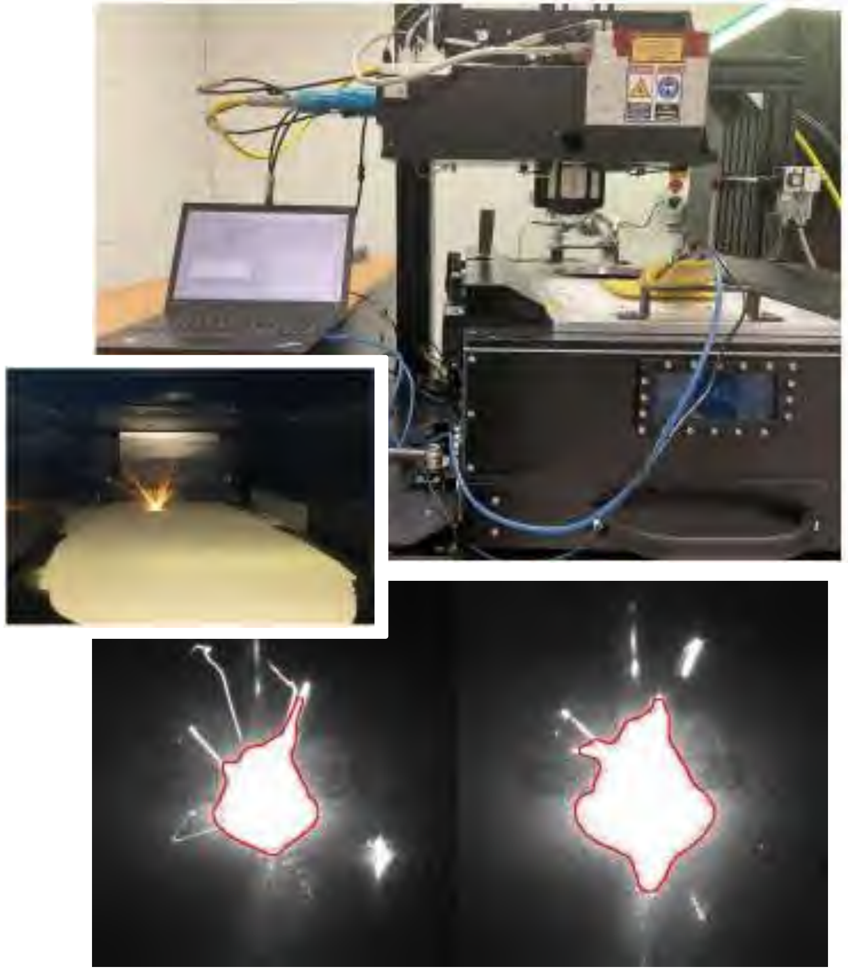
Hardware Keeps the Controls Engineer Honest



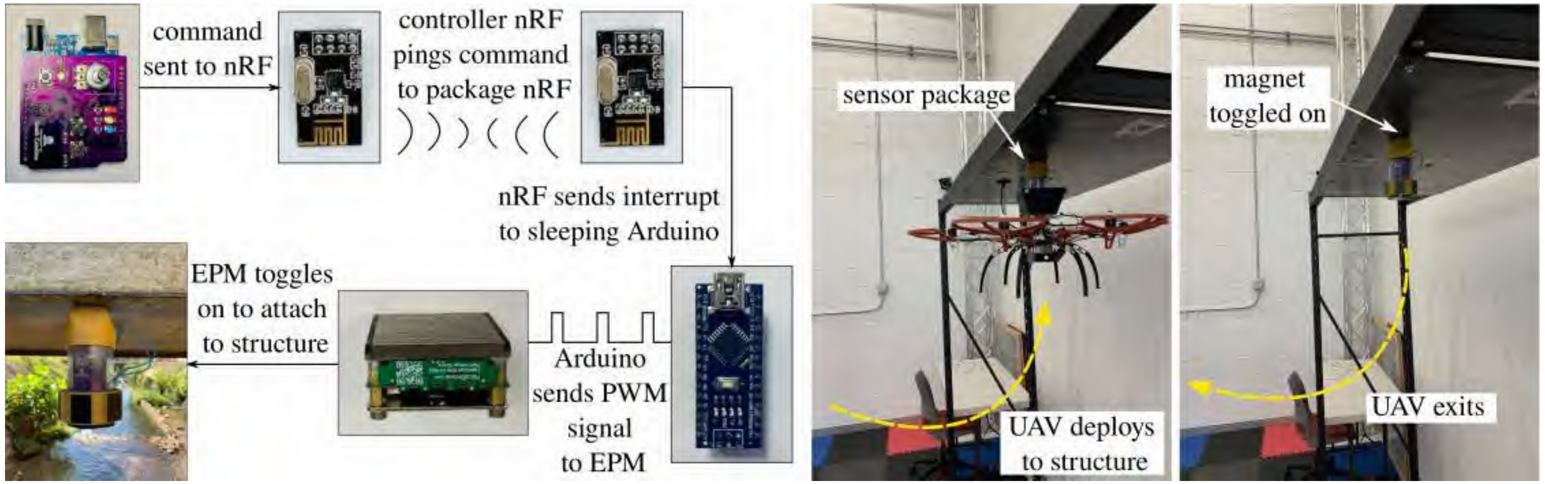
ARTS-Lab at the University of South Carolina

ARTS-Lab Projects

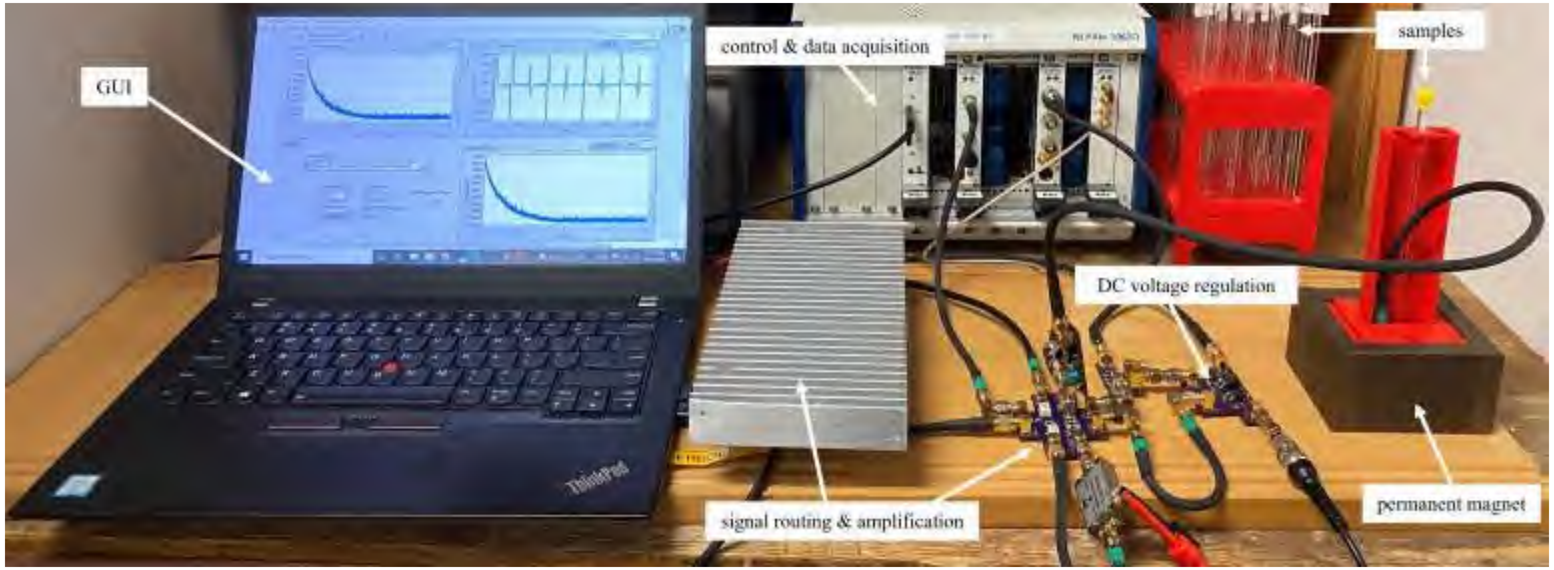
Additive Manufacturing



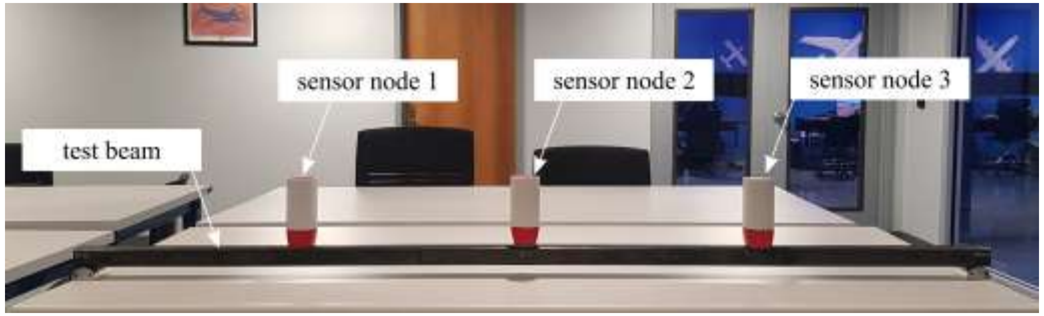
UAV Deployable Sensors

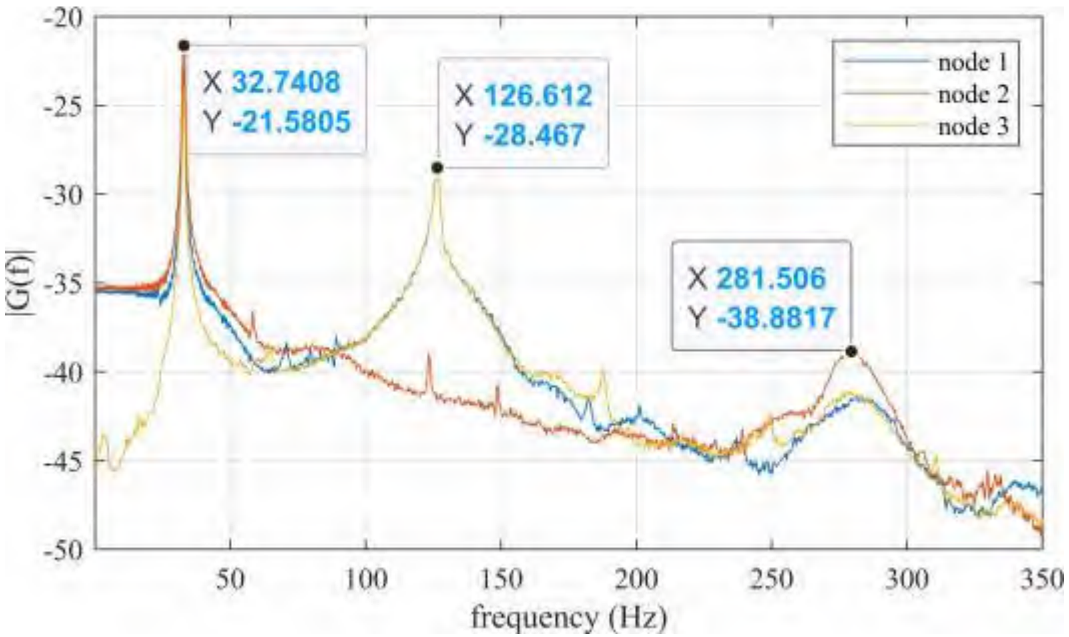


Nuclear magnetic resonance (NMR)-based sensing



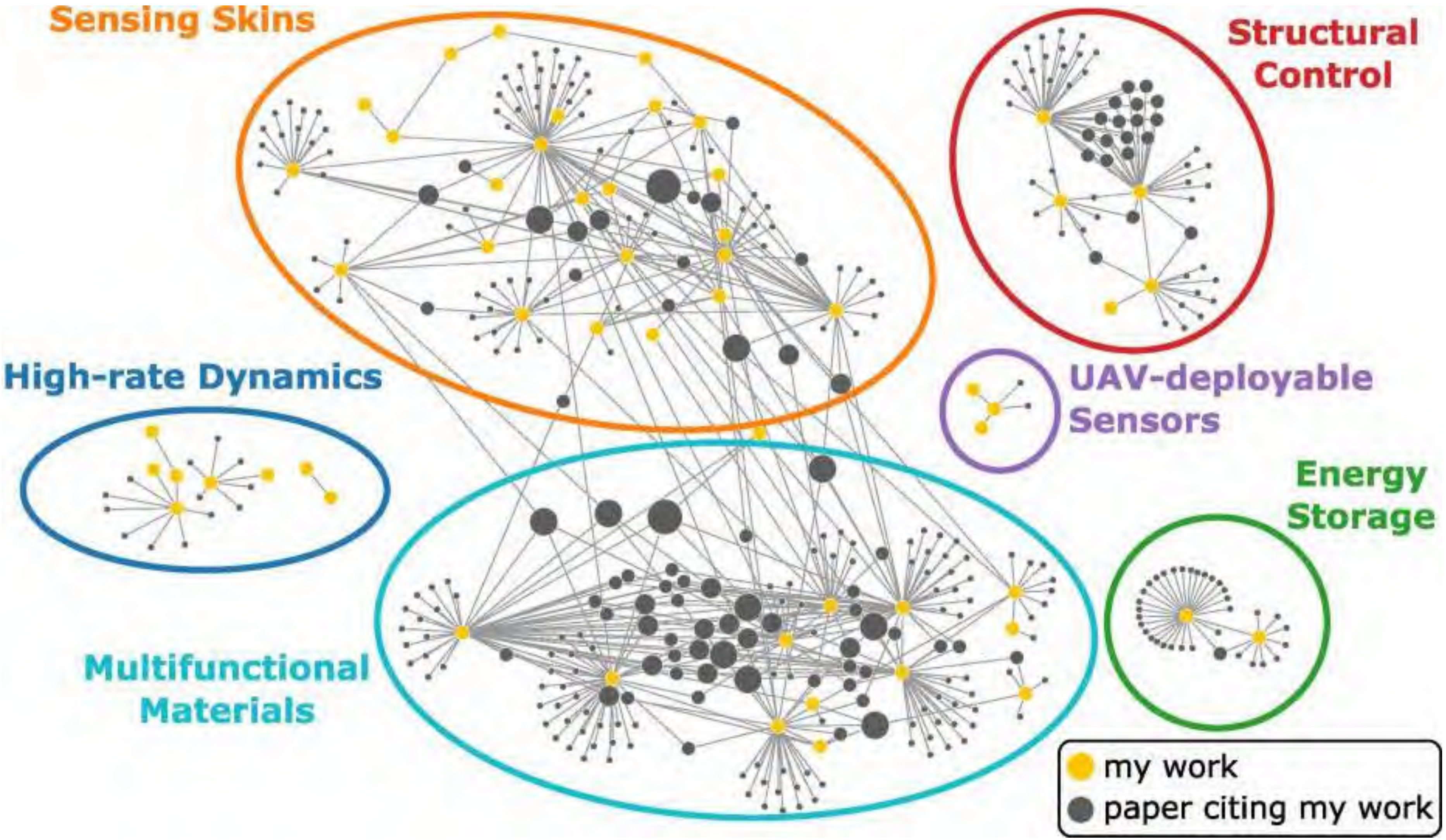
UAV Deployable Sensors for SHM





Publications (Special for University of Perugia)

- I worked on multi-functional materials in Perugia in 2016 and 2017. It is interesting to see what this research grew into.
- One never knows where research will take them.



High-rate Digital Twins

Structures Experiencing High-Rate Dynamic Events

Applications:

1. Vehicle collision
2. Blast mitigation
3. Ballistic packages
4. Hypersonic vehicles
5. Hard Target Penetrating Weapons

Vehicle Collision


Active Blast Mitigation


Ballistics Packages

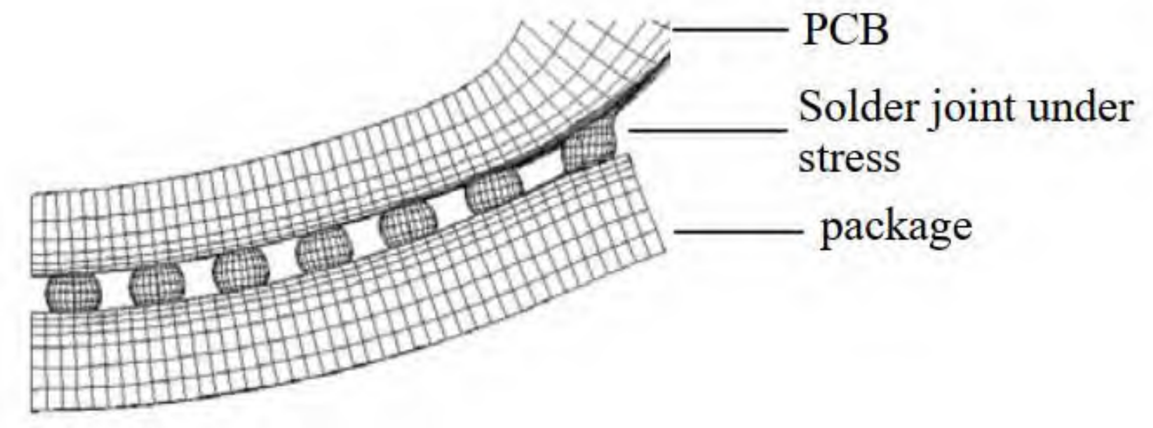

Hypersonic Vehicles


Hard Target Penetrating Weapons

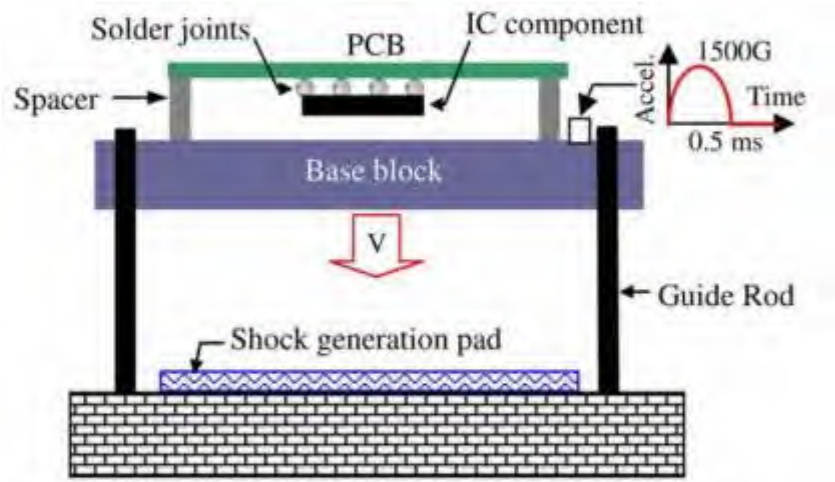
Typical PCB Failure Mechanisms under Shock

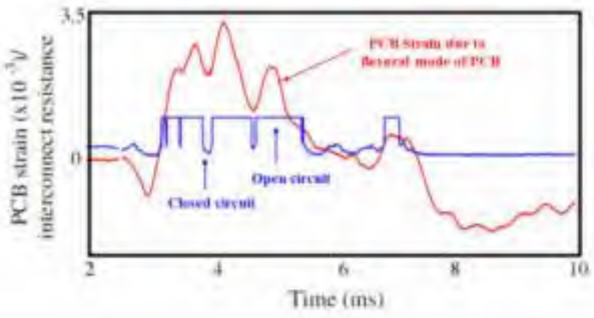
PCB failures under shock are caused by:

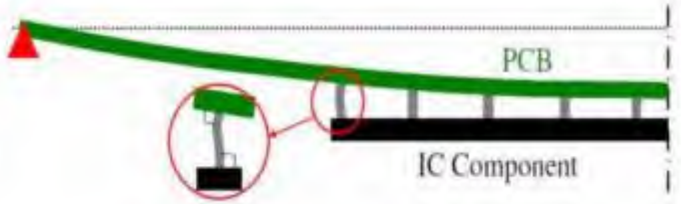
- Bending of the base PCB board, causing stresses to build up at the solder balls.
- Adhesion challenges of masses (components) accelerating away from the PCB.



Seah, S. K. W., Wong, E. H., Ranjan, R., Lim, C. T., and Mai, Y. W., 2005, "Understanding and testing for drop impact failure," ASME Pacific Rim Technical Conference and Exhibition on Integration and Packaging of MEMS, NEMS, and Electronic Systems, pp. 1089-1094.







Chen, Zhuo. *Effective Mitigation of Shock Loads of Embedded Electronics in Smart Ammunitions by Polymeric Encapsulation*. Diss. University of Toronto (Canada), 2014.

Wong, E. H., Yiu-Wing Mai, and Matthew Woo. "Analytical solution for the damped-dynamics of printed circuit board and applied to study the effects of distorted half-sine support excitation." IEEE Transactions on advanced packaging 32.2 (2009): 536-545.

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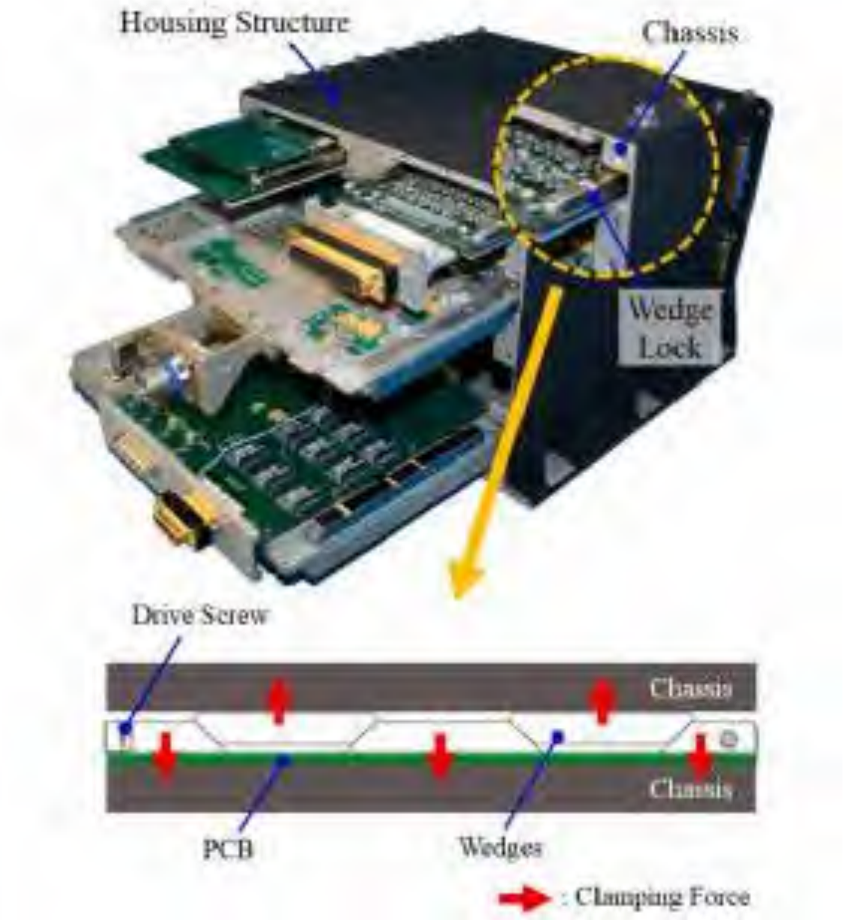
Broader applications: PCB Components under shock

Driving applications include:

- PCBs in potted containers.
- PCBs In wedge-lock housings.



Park, Tae-Yong, et al. "High-damping PCB implemented by multi-layered viscoelastic acrylic tapes for use of wedge lock applications." *Engineering Fracture Mechanics* 241 (2021): 107370.

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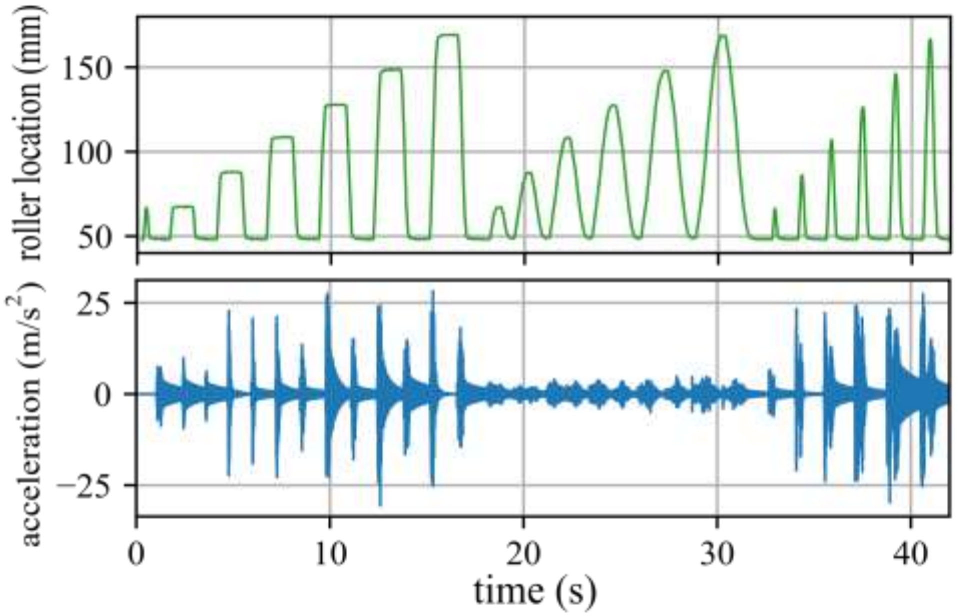
Experimental System used for Validation

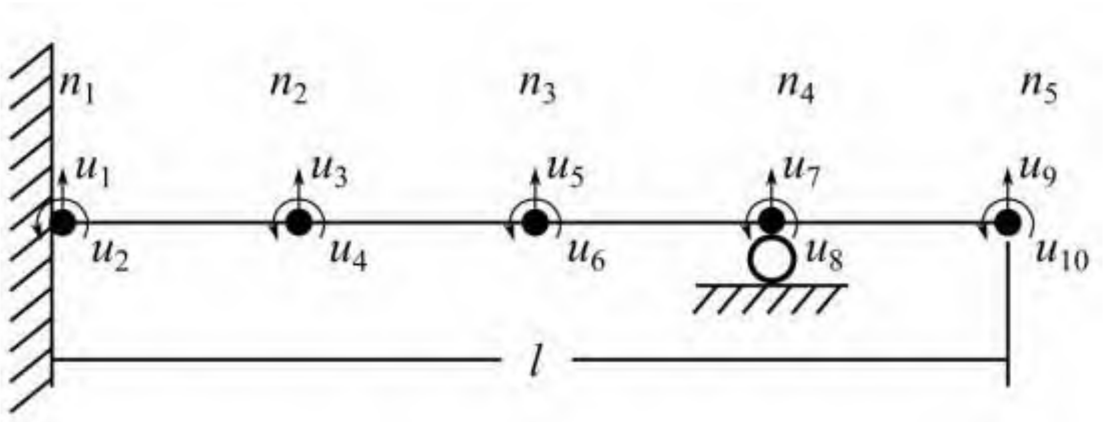
DROPBEAR experimental testbed:

- The Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research (DROPBEAR) was used to generate the experimental data in this work.
- Cantilever beam with a controllable roller to alter the state.
- Acceleration and pin location are recorded.
- Dataset available on GitHub at: https://github.com/High-Rate-SHM-Working-Group/Dataset-2-DROPBEAR-Acceleration-vs-Roller-Displacement



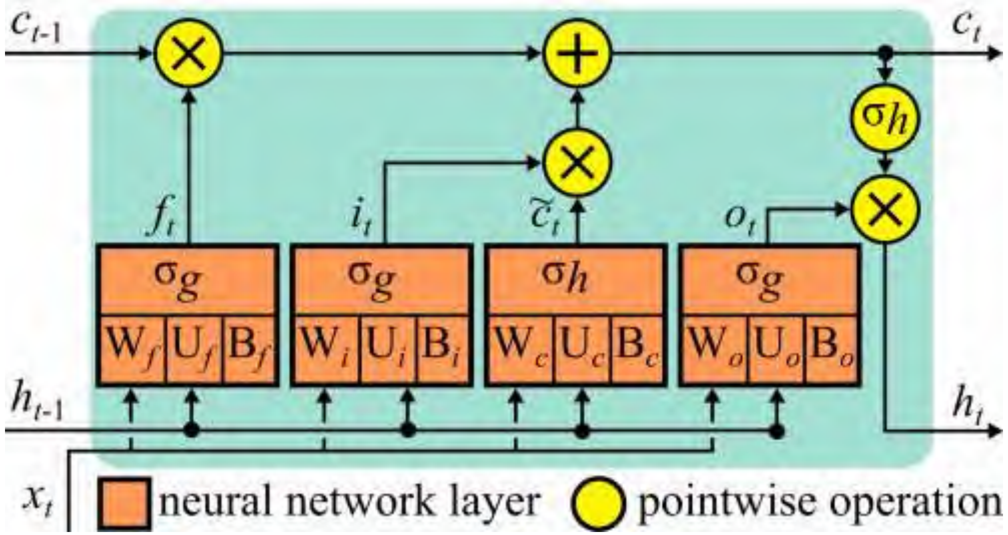
Two approaches

Physics-based Model Updating



$$[M^p]=\frac{\rho_p A_p l_p}{420}\begin{bmatrix} 156 & 22l_p & 54 & -13l_p \\ 22l_p & 4l_p^2 & 13l_p & -3l_p^2 \\ 54 & 13l_p & 156 & -22l_p \\ -13l_p & -3l_p^2 & -22l_p & 4l_p^2 \end{bmatrix} [K^p]=\frac{E_p I_p}{l_p}\begin{bmatrix} \frac{12}{l_p^2} & \frac{6}{l_p} & -\frac{12}{l_p^2} & \frac{6}{l_p} \\ \frac{6}{l_p} & 4 & -\frac{6}{l_p} & 2 \\ -\frac{12}{l_p^2} & -\frac{6}{l_p} & \frac{12}{l_p^2} & -\frac{6}{l_p} \\ \frac{6}{l_p} & 2 & -\frac{6}{l_p} & 4 \end{bmatrix} \quad (13)$$

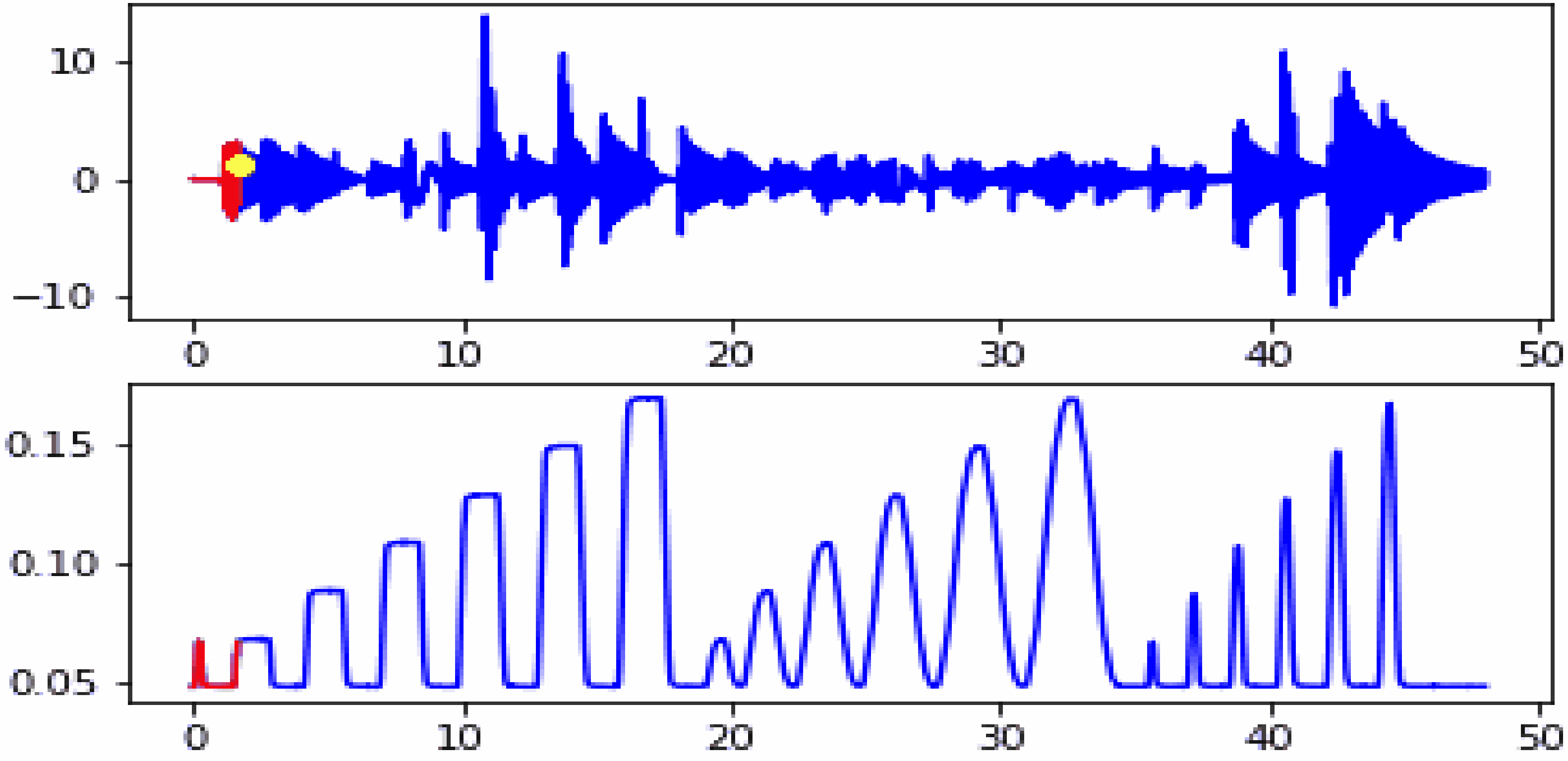
Data Driven Modeling



Goal is to track the state of the structure

For this:

- The position of the roller is analogous to the state of the structure.
- Accelerometer signal is the input, roller position is the output.



Physics-based Model Updating
(Eigen Value Problem)

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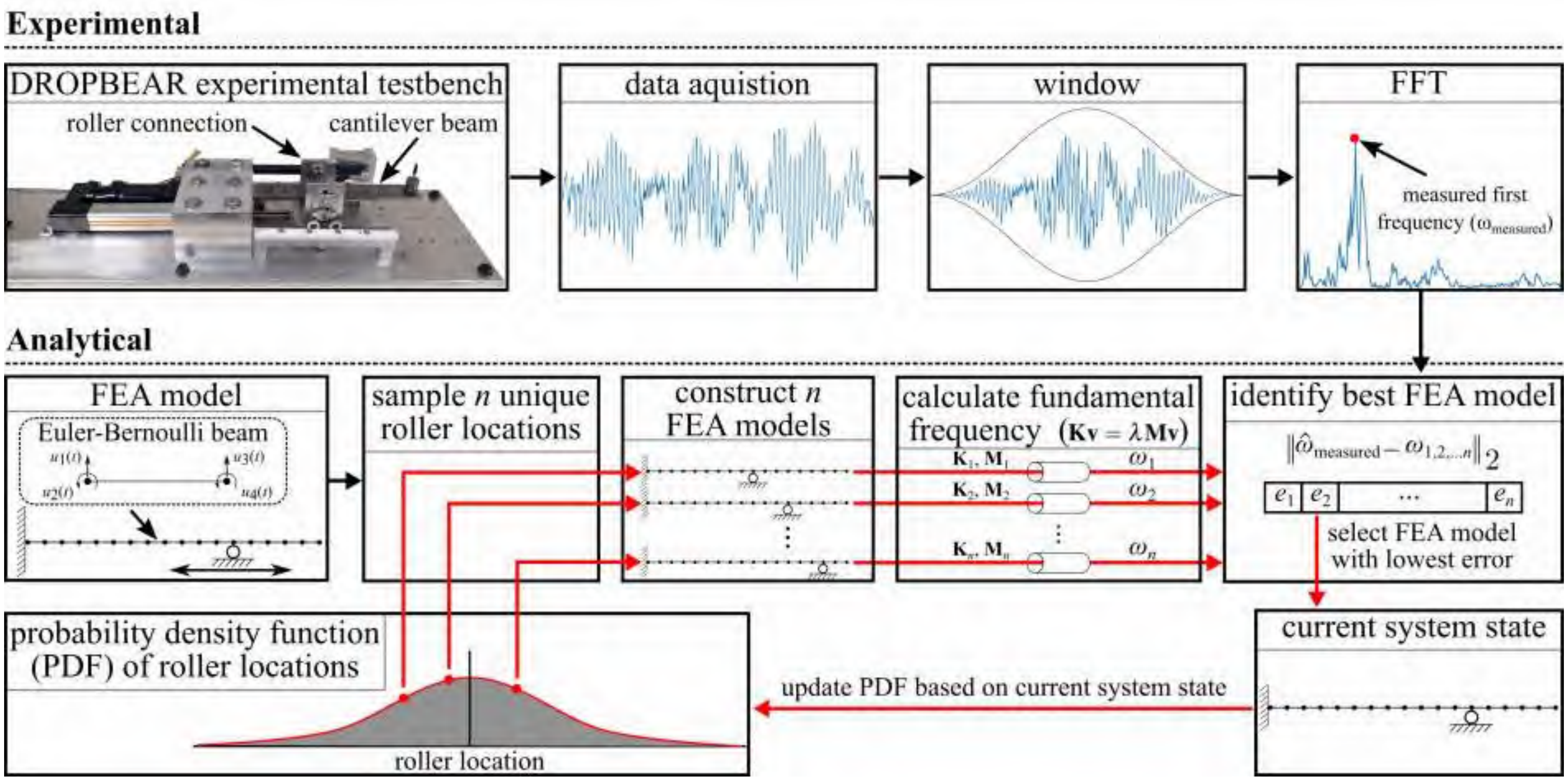
Real-Time Model Updating Through Error Minimization

A frequency-based model updating technique was developed to update an FEA model of the system.



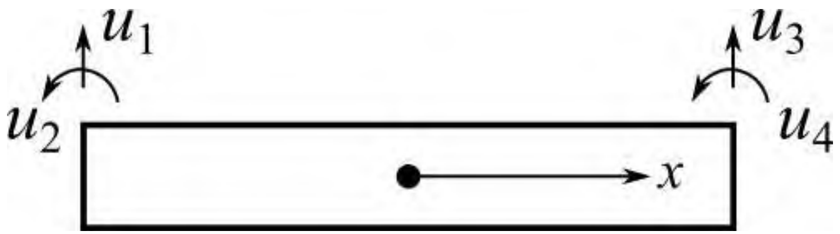
Downey A., et al,. "Millisecond Model Updating for Structures Experiencing Unmodeled High-Rate Dynamic Events" *Mechanical Systems and Signal Processing* ***138***, 2020

Background: Euler-Bernoulli Beam

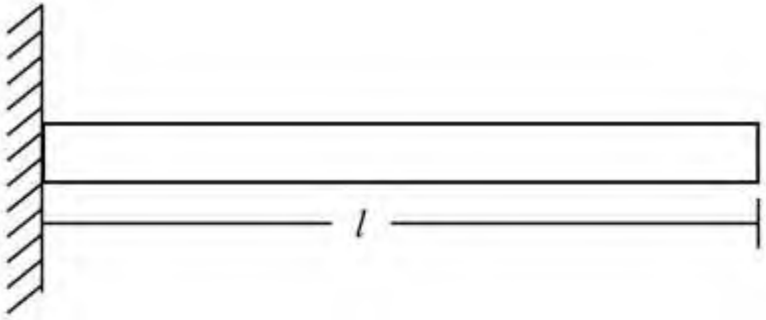
Euler–Bernoulli beam theory:

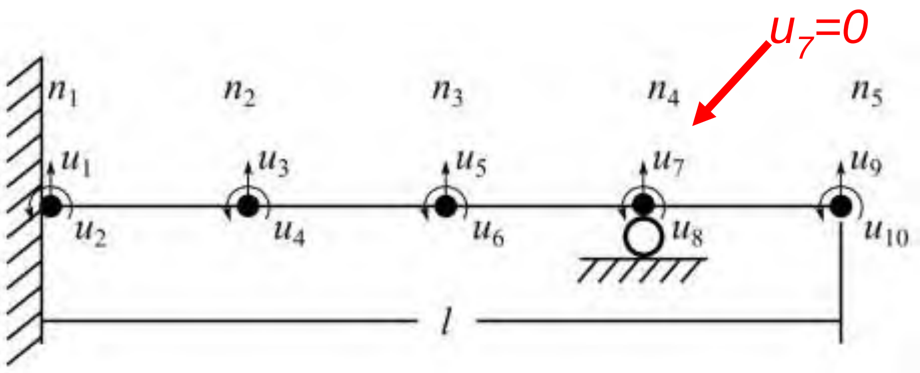
- Is a linear approximation of the response of a beam under load.
- Only applicable to small loads applied in the lateral direction.
- Plane sections remain plane and normal to the axis of the beam.
- Provides better predictions for thin beams than for thick beams (length-to-thickness < 20).

Euler–Bernoulli Beam Element



$$[M^p]=\frac{\rho_p A_p l_p}{420}\begin{bmatrix} 156 & 22l_p & 54 & -13l_p \\ 22l_p & 4l_p^2 & 13l_p & -3l_p^2 \\ 54 & 13l_p & 156 & -22l_p \\ -13l_p & -3l_p^2 & -22l_p & 4l_p^2 \end{bmatrix} \quad [K^p]=\frac{E_p I_p}{l_p}\begin{bmatrix} \frac{12}{l_p^2} & \frac{6}{l_p} & -\frac{12}{l_p^2} & \frac{6}{l_p} \\ \frac{6}{l_p} & 4 & -\frac{6}{l_p} & 2 \\ -\frac{12}{l_p^2} & -\frac{6}{l_p} & \frac{12}{l_p^2} & -\frac{6}{l_p} \\ \frac{6}{l_p} & 2 & -\frac{6}{l_p} & 4 \end{bmatrix} \quad (13)$$





Background: Modal Analysis

Modal analysis is used to find the mode shapes and frequencies of a structure during free vibration.

Starting with the equation of motion:

$$\mathbf{M}\ddot{x} + \mathbf{C}\dot{x} + \mathbf{K}x = 0$$

the damping coefficient can be ignored as its effect on the natural frequency is less than 0.0005%, resulting in the expression:

$$\mathbf{M}\ddot{x} + \mathbf{K}x = 0$$

assuming a temporal solution:

$$x(t) = \Phi\big(A_n \cos(\omega_n t) + B_n sin(\omega_n t)\big)$$

yields the following expression:

$$\Big(-\mathbf{\Omega}_n^2\mathbf{M}\Phi + \mathbf{K}\Phi_n\Big)q_n(t) = 0$$

where $q_n(t)$=0 is a trivial solution, therefore the eigenvalues and eigenvectors are solved for using the general eigenvalue problem formulation:

$$\mathbf{K}\Phi_n = \lambda_n \mathbf{M}\Phi_n$$

where:

$$\lambda_n = \mathbf{\Omega}_n^2$$

TIME CONSUMING

COMPETITION

and:

$$\omega_n = \sqrt{\lambda_n}$$

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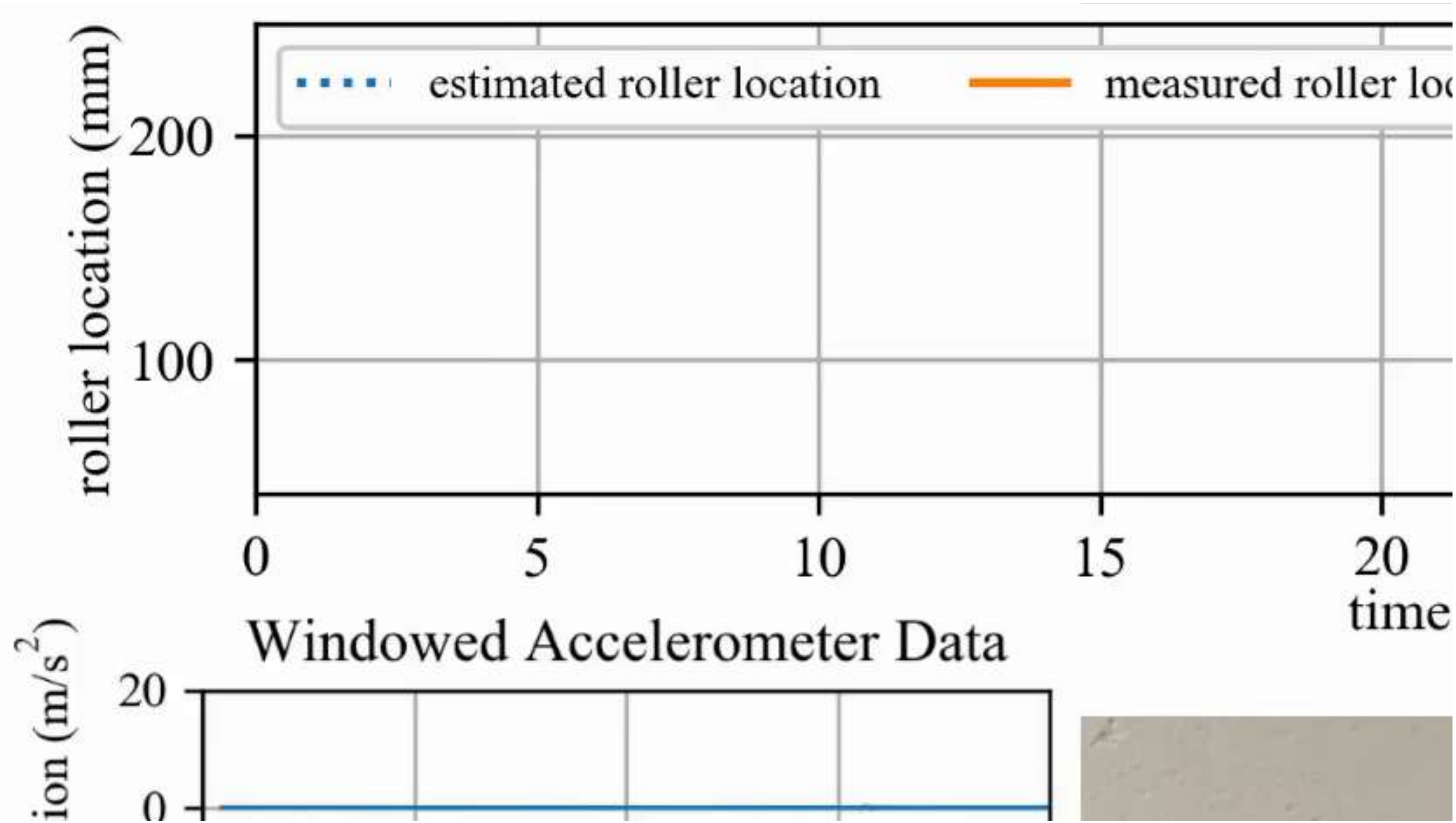

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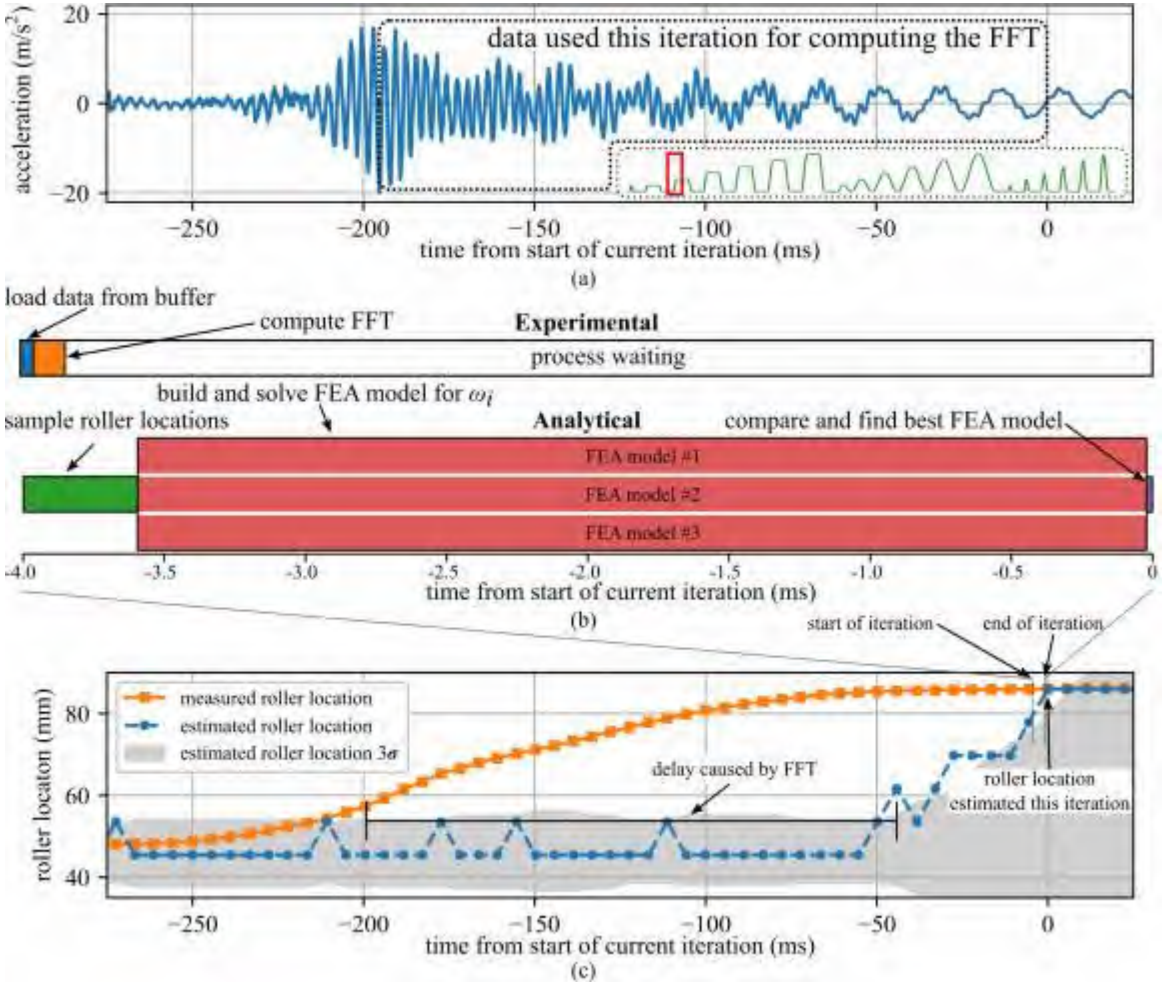
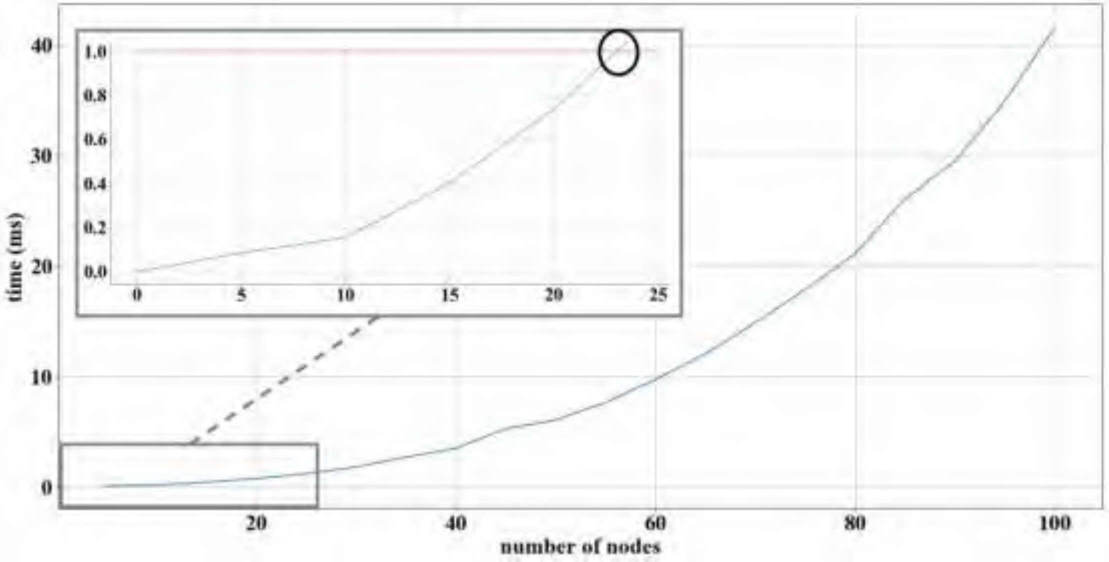
Experimental Results: Algorithm Timing

- General Eigenvalue solutions accurately estimate the state of the DROPBEAR.
- Solving for the system's frequencies accounted for 90% of algorithm iteration time.



FEA model Limited to 23 nodes



Carroll, M., Downey, A., Dodson, J., Hong, J. and Scheppegrell, J., "Analysis of Computation Speeds of Eigenvalue Solutions for High-Rate Structural Health Monitoring."

Eigen Value Problem - Can we just solve it faster?

- General Eigenvalue solutions are a well studied problem.
- Hardware accelerators do exist, but their throughput is limited by communication bandwidth.

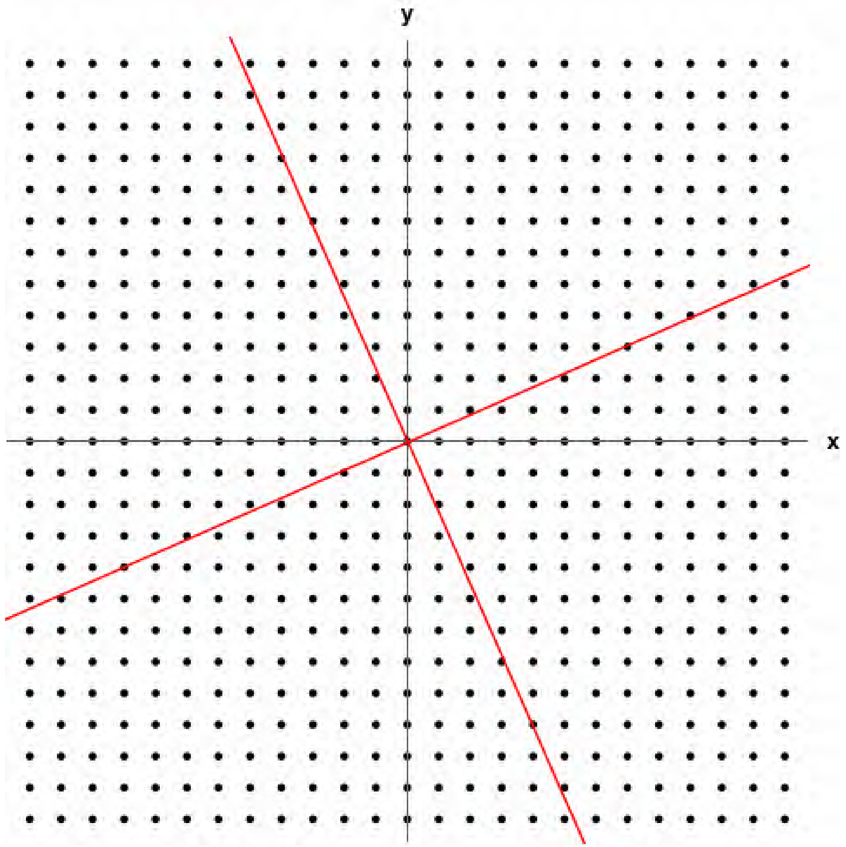
$$\mathbf{M}_1\ddot{x} + \mathbf{K}_1 x = 0$$

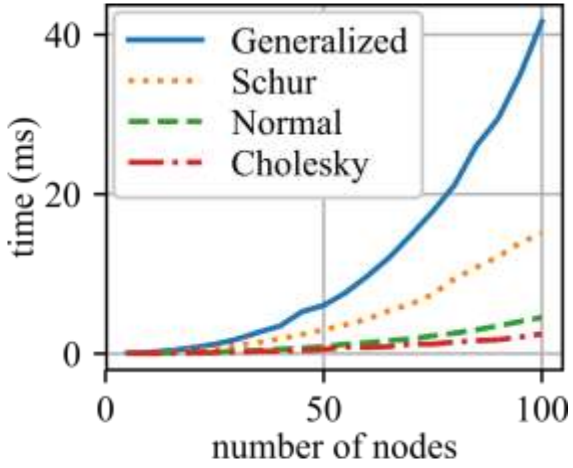
$$\det[\mathbf{K}_1 - \boldsymbol{\lambda}\mathbf{M}_1] = 0$$

$$[\mathbf{K}_1 - \boldsymbol{\lambda}\mathbf{M}_1]\mathbf{U}_1 = 0$$

$$\boldsymbol{\lambda} = \begin{bmatrix} \omega_1^2 & 0 & 0 & 0 \\ 0 & \omega_2^2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \omega_n^2 \end{bmatrix}$$

$$\mathbf{U}_1 = [\vec{u}_1^1 \quad \vec{u}_2^1 \quad \cdots \quad \vec{u}_n^1]$$





Developed a specialized Cholesky-Jacobi method formulated specifically for this challenge; a 66 node FEA model can be solved for within the 1 ms.

Local Eigenvalue Modification Procedure (LEMP)

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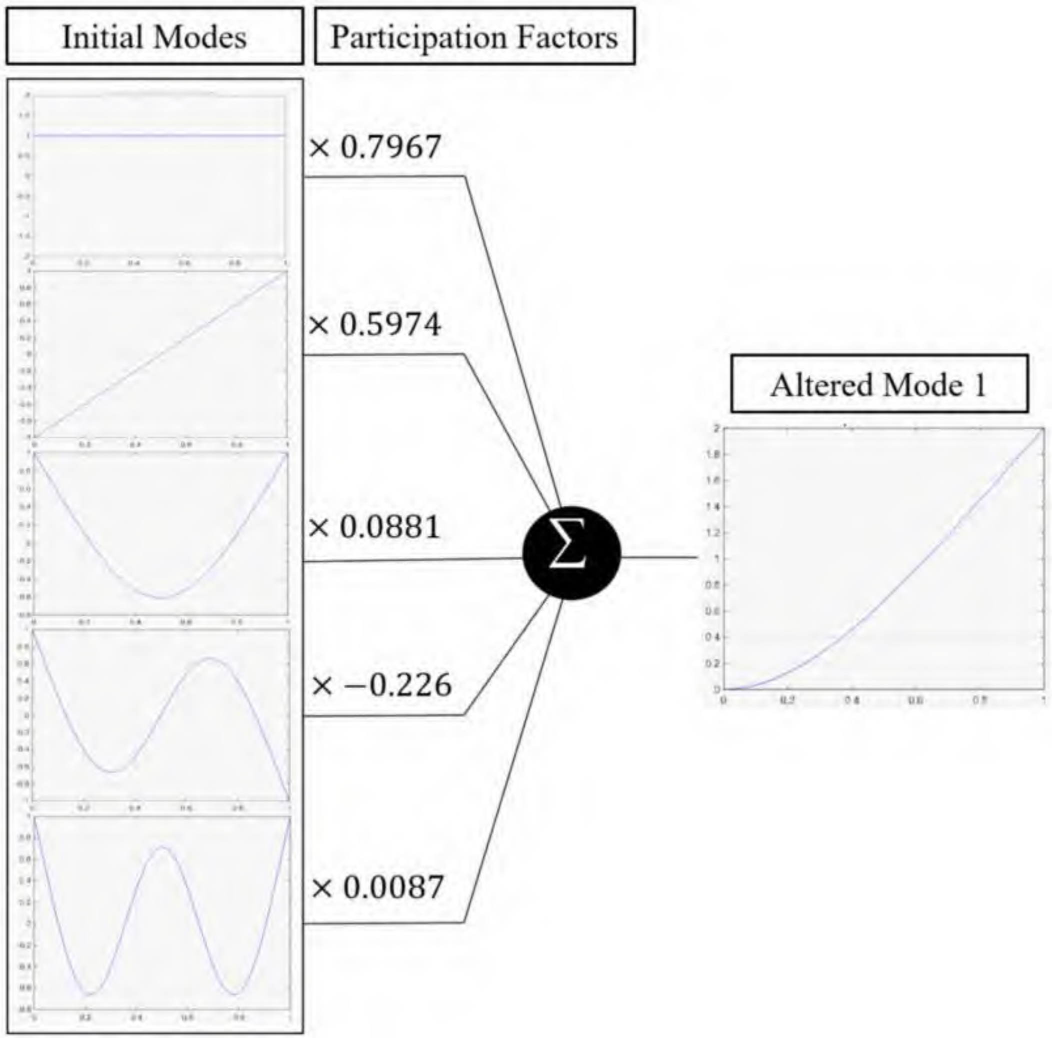
Local Eigenvalue Modification Procedure (LEMP)

Developed by Wesseinburger in 1968:

- Identifies physical changes to the system such as mass, stiffness, and damping using changes such as frequencies or mode shapes.
- Model the altered state as a mixture of the initial state and changes made to the initial state.
- Reduces the GE equation to a set of second-order equations.

Mode	Frequency (Hz)	Mode type	Shape
1	37.6956	Bending-Y	
2	248.561	Bending-Y	
3	713.463	Bending-Y	
4	1416.40	Bending-Y	
5	2353.62	Bending-Y	

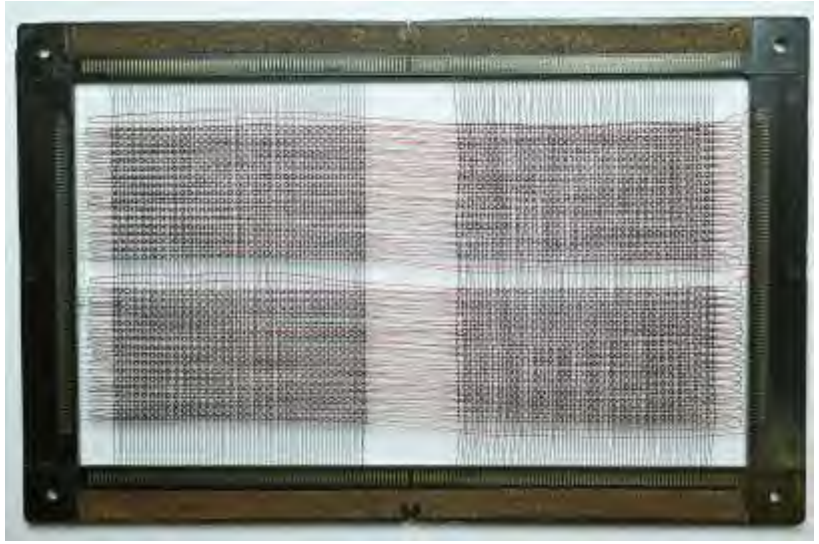


Avitabile, P., "*Twenty Years of Structural Dynamic Modification- A Review*," *Sound and Vibration,* pp. 14-25. 2003
Drnek, C. R., "*Local eigenvalue modification procedure for real-time model updating of structures experiencing high-rate dynamic events*," (2020).

A “perspective” on computing in 1968

Computing in 1968:

- Machine time was expensive (if even obtainable).
- Extensive data augmentation and “pre-processing” was affordable.
- The IBM Systems 360 Model was cutting edge.



Magnetic-core memory, probably from a 360

IBM System/360 Model 30 CPU (red, middle of picture), tape drives to its left, and disk drives to its right, at the Computer History Museum

LEMP usage in the ‘70s and ’80s

LEMP enabled these calculations to be done very efficiently on very slow desktop computers.

- Structural Measurements Systems (SMS) sold a custom hardware and software setup.
- This was before the “personal computer” stage.

HP1000/A700 w/DIFA modal analysis system

SMS modal software called SDM used LEMP

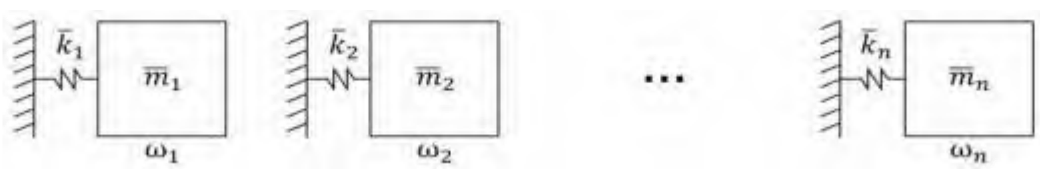
HP3000 desktop running “Rocky Mountain BASIC”

HP5423 first dedicated FFT/Modal system - 1979

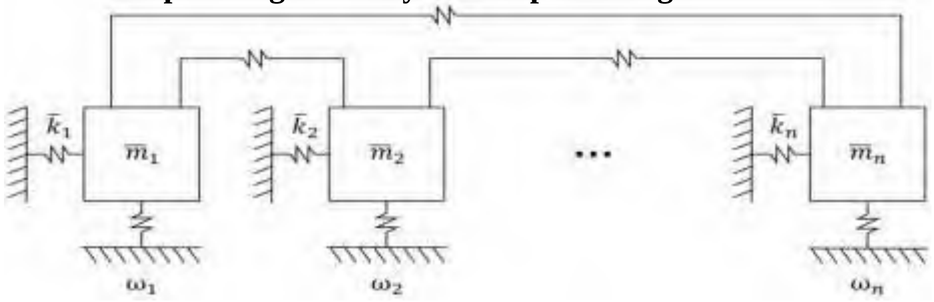
All images and knowledge curtesy of Peter Avitabile Professor Emeritus, Co-Director - Structural Dynamics & Acoustic Systems Laboratory at the University of Massachusetts Lowell

Local Eigenvalue Modification Procedure (LEMP)

n independent single DOF systems representing the initial state



Coupled single DOF systems representing the altered state



Initial State → Modification → Altered State

Physical Space: $[\mathbf{M}_1], [\mathbf{K}_1]$ → $[\Delta\mathbf{M}_{12}], [\Delta\mathbf{K}_{12}]$ → $[\mathbf{M}_2], [\mathbf{K}_2]$ — '*n*' Physical DOF

Modal Transformation: $\{x\} = [U_1]\{p_1\}$ $\{x\} = [U_2]\{p_2\}$ — *m<<n*

$$\frac{-1}{\alpha} = \sum_{r=1}^{m} \frac{v_r^2}{\omega_r^2 - \Omega_r^2}$$

Solved using Divide and Conquer method

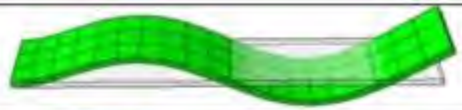
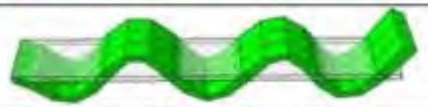
Modal Space: $[\omega_1^2], [U_1]$ → $\{p_1\} = [U_{12}]\{p_2\}$ → $[\Omega_2^2], [U_2]$ — '*m*' Modal DOF

Avitabile, P., "*Twenty Years of Structural Dynamic Modification- A Review*," *Sound and Vibration,* pp. 14-25. 2003
Drnek, C. R., "*Local eigenvalue modification procedure for real-time model updating of structures experiencing high-rate dynamic events*," (2020).

Determine Contributing Modes

For this problem:

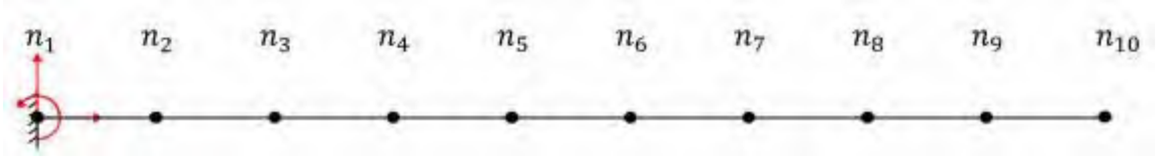
- The modes used to describe the system were limited to modes 1-4.
- Higher modes are hard to track experimentally.
- Only one sensor measuring vertical acceleration near the tip of the beam is used, therefore, only “Bending-Y” type modes can be used.
- With these first four modes, we can describe the system dynamics.

Mode	Frequency (Hz)	Mode type	Shape
1	37.6956	Bending-Y	
2	248.561	Bending-Y	
3	713.463	Bending-Y	
4	1416.40	Bending-Y	
5	2353.62	Bending-Y	
6	3519.66	Bending-Z	
7	4918.50	Torsional	
8	6569.90	Bending-Y	
9	8422.02	Bending-Y	
12	15420.6	Torsional	

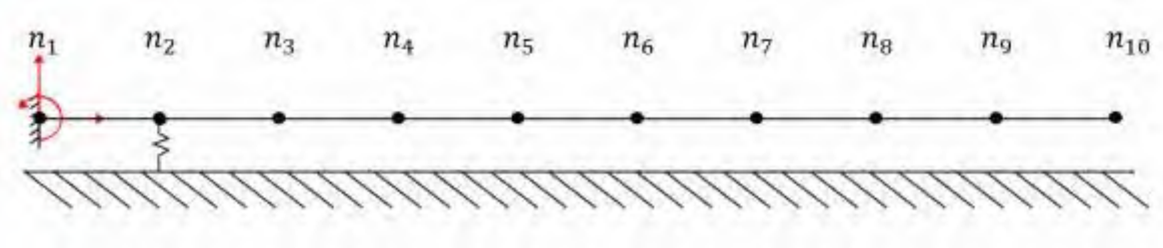
Changing States

- LEMP models one change in the system at a time.
- Still need to solve the GE problem once, then it can be updated with each successive step.

Initial State:



Altered State:



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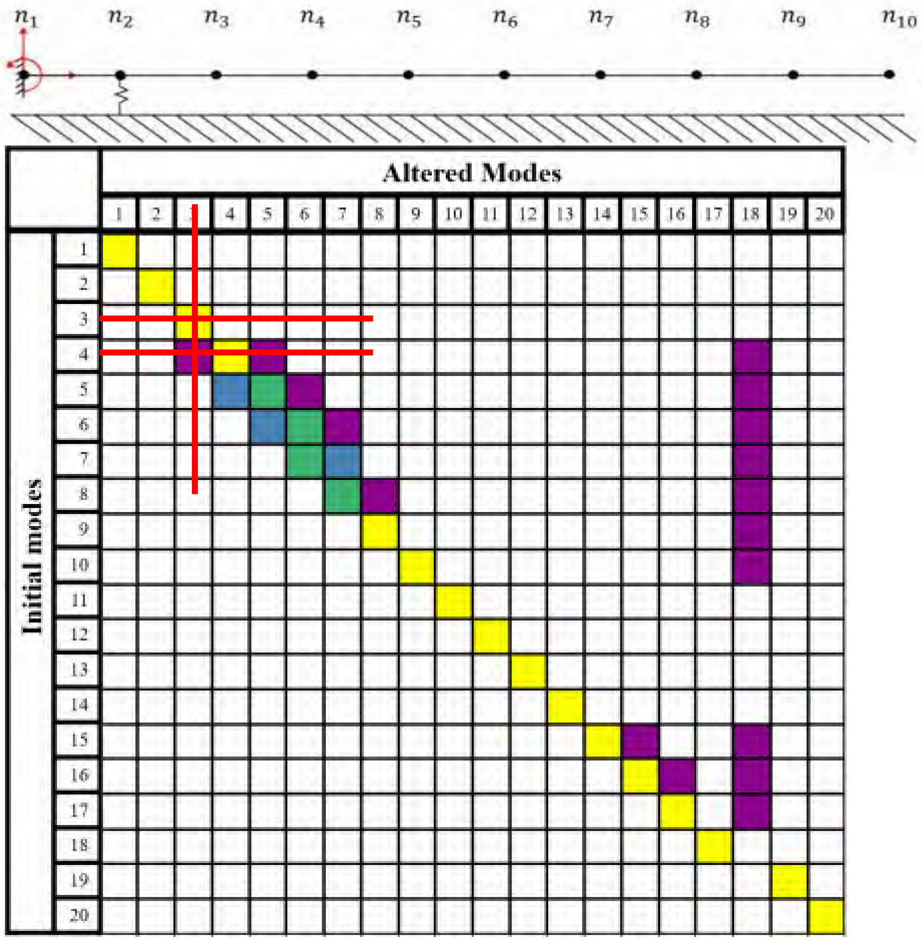
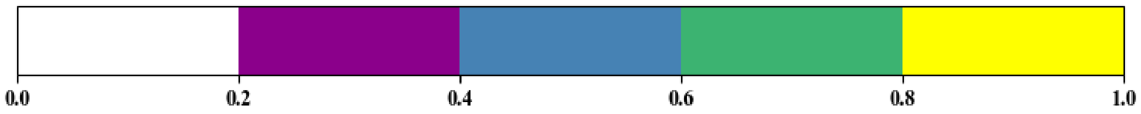
Modal Contributions



Modal Participation Factor Contribution Key



The altered Mode 3 is made up of:

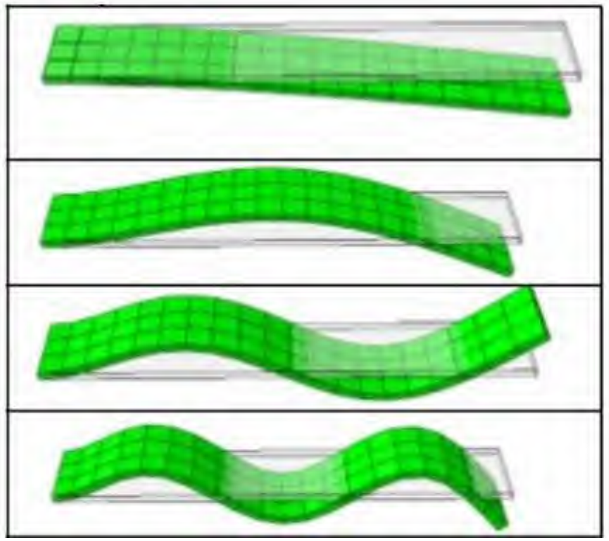
- the initial mode 3
- the initial mode 4

Mode 1

Mode 2

Mode 3

Mode 4

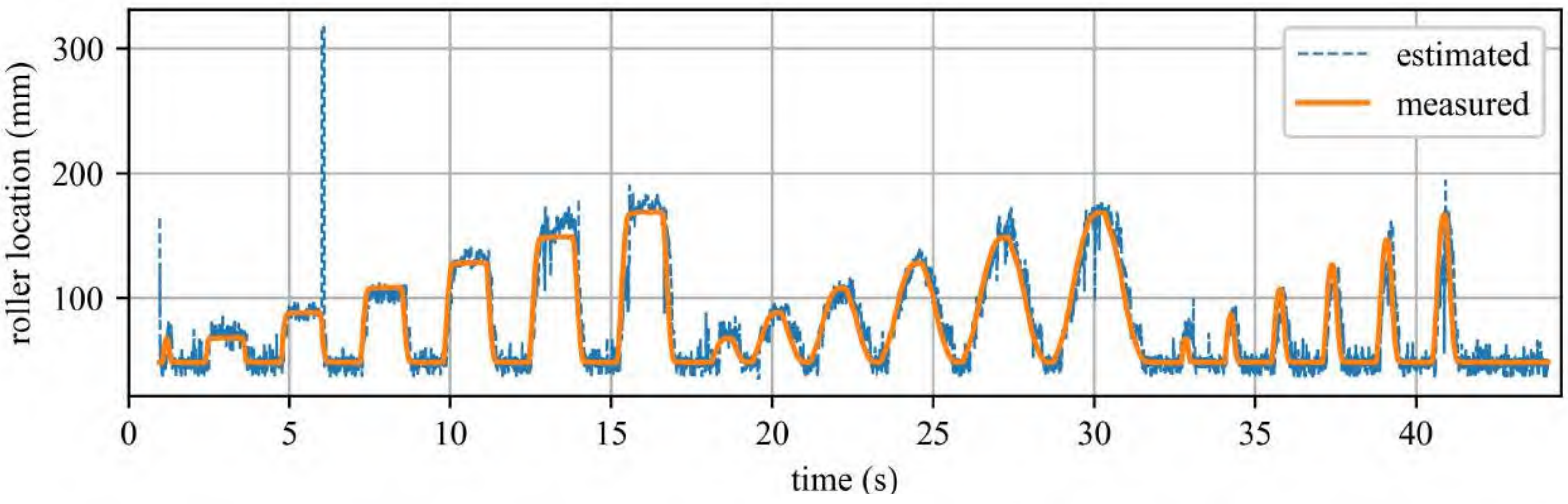


LEMP State Estimation Results

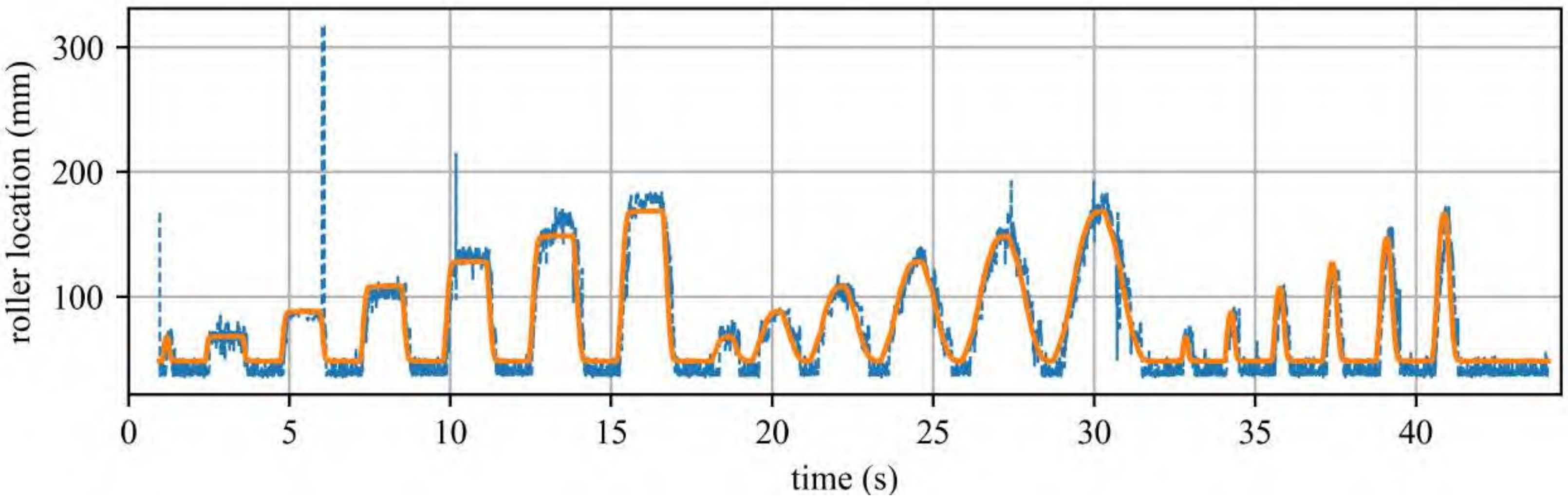
LEMP has been shown to:

- Have similar accuracy to the generalized eigenvalue solver
- Be robust to sensor noise
- Be capable of working with various error estimator developed for the project

generalized eigenvalue solver



LEMP solver



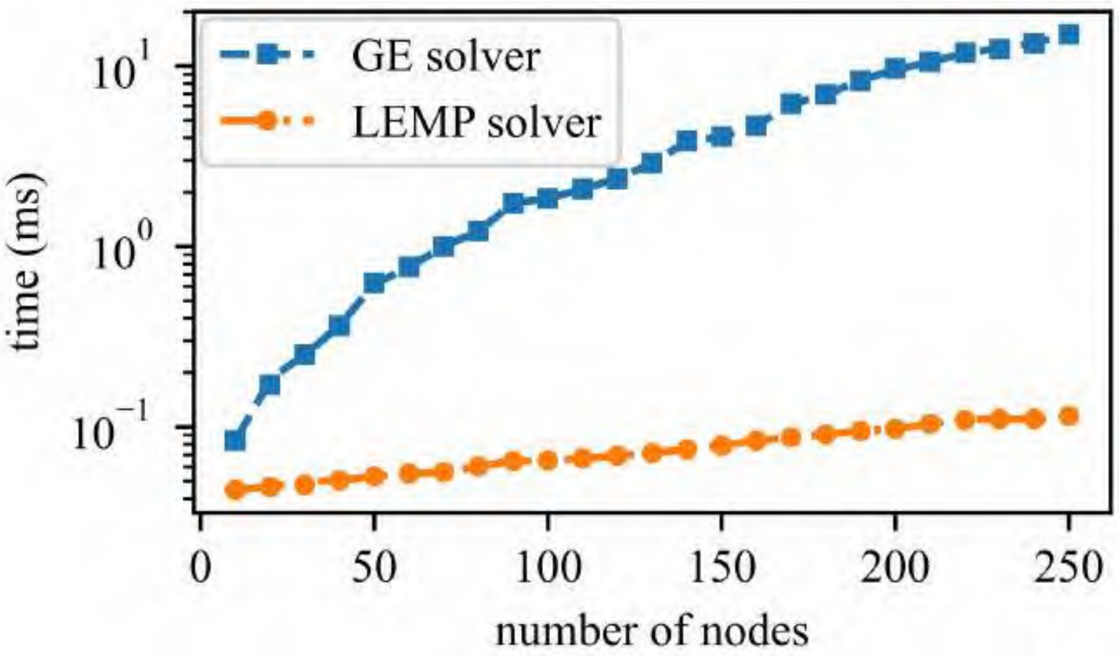
LEMP Algorithm Timing

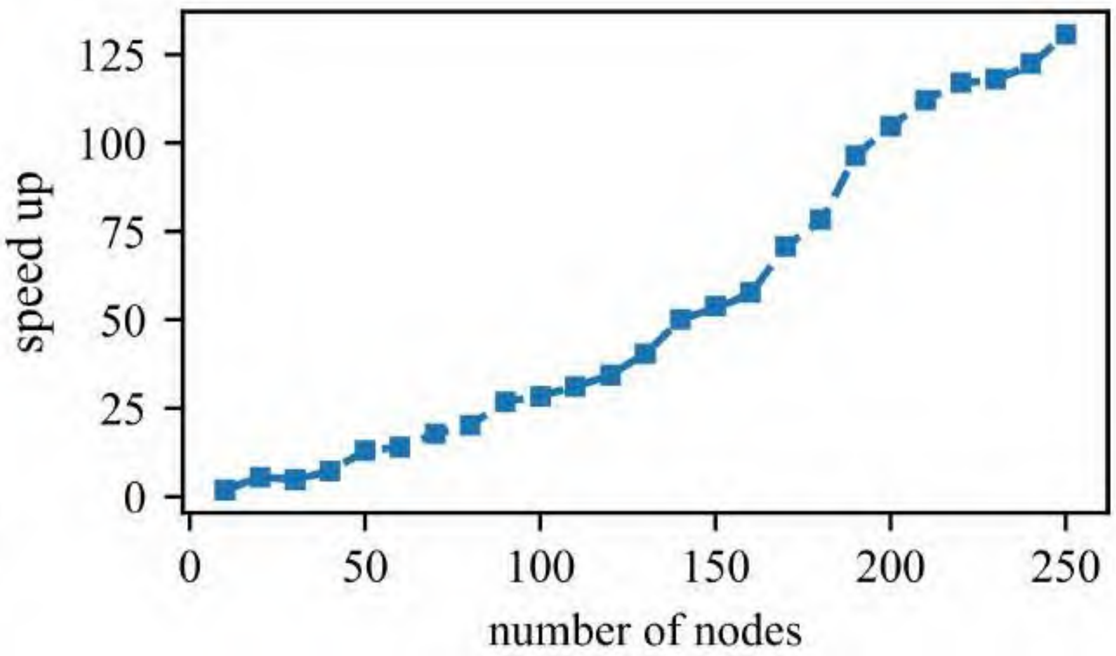
So far with LEMP we have been able to obtain:

- Algorithm seed up of up to 120 for 1D structures.
- Sub 1 ms model updating for 250.

We plan to work on an FPGA-based implementation.

Blast Mitigation | LINE-X





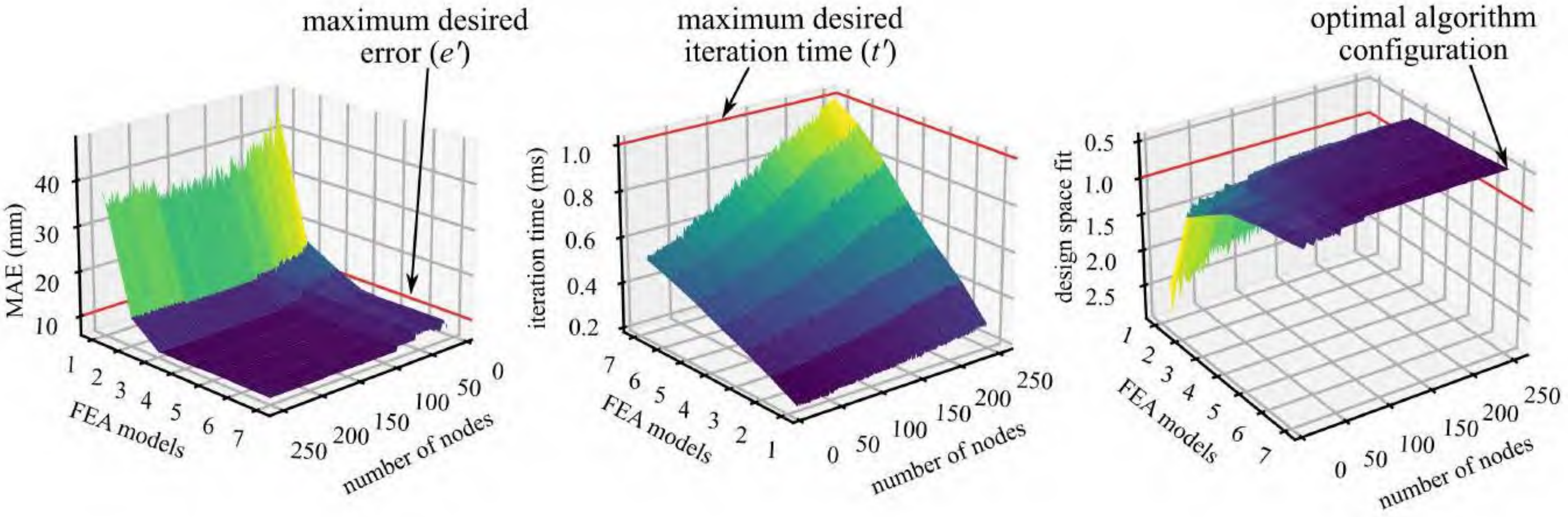
LEMP Algorithm Perforce Space

Also looking at multi-objective optimization, to find the optimal algorithm configuration parameters (**P**), considering:

- error – *e*, and allowed error *e’*
- time step – *t*, and allowed time step *t’*

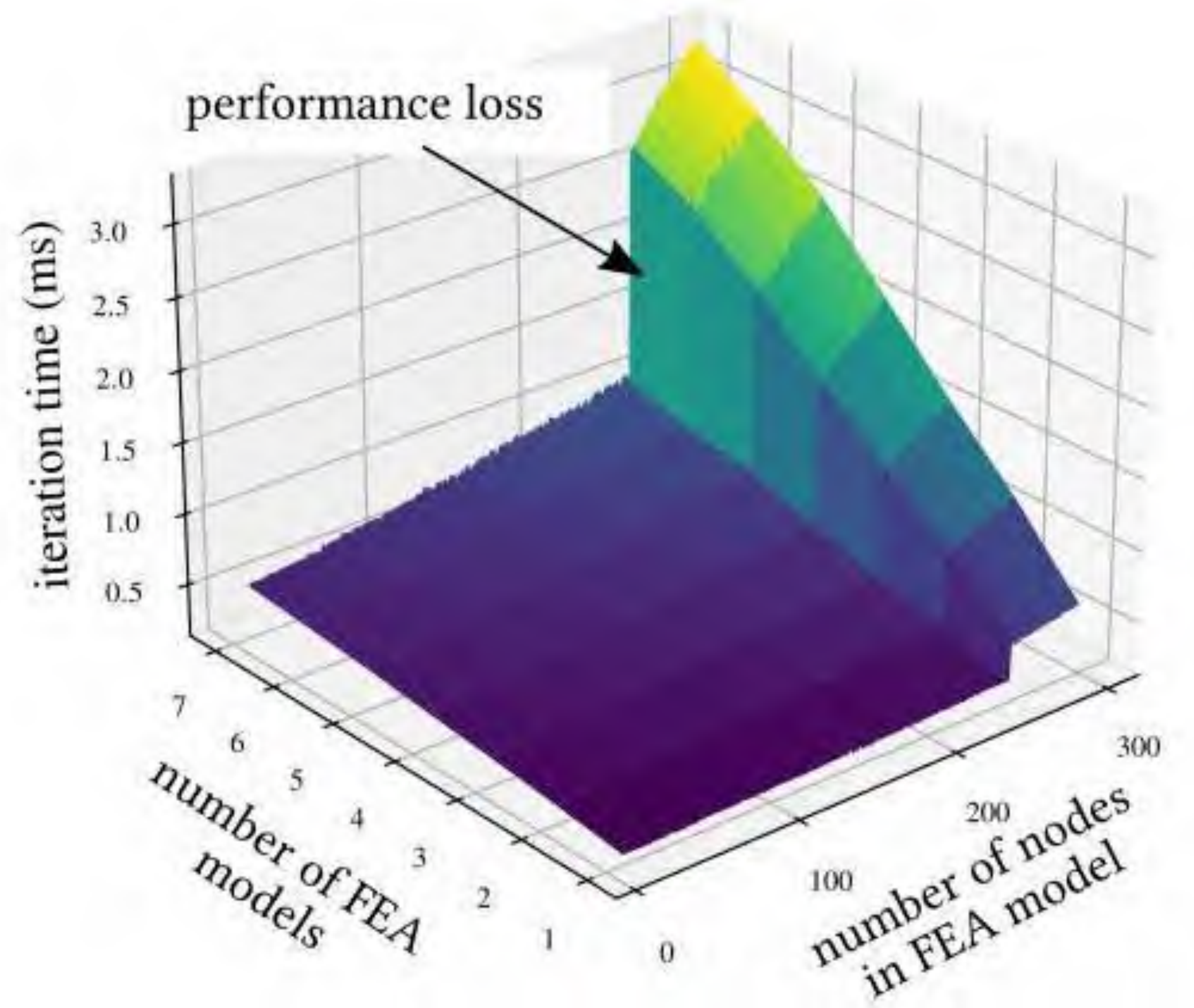
$$\underset{\mathbf{P}}{\text{minimize}}\ \text{fit} = (1-\alpha)\frac{e(\mathbf{P})}{e'} + \alpha\frac{t(\mathbf{P})}{t'}$$

$$\text{subject to } \mathbf{P} = [p_{\text{nodes}}, p_{\text{models}}] \in \mathbb{P}$$

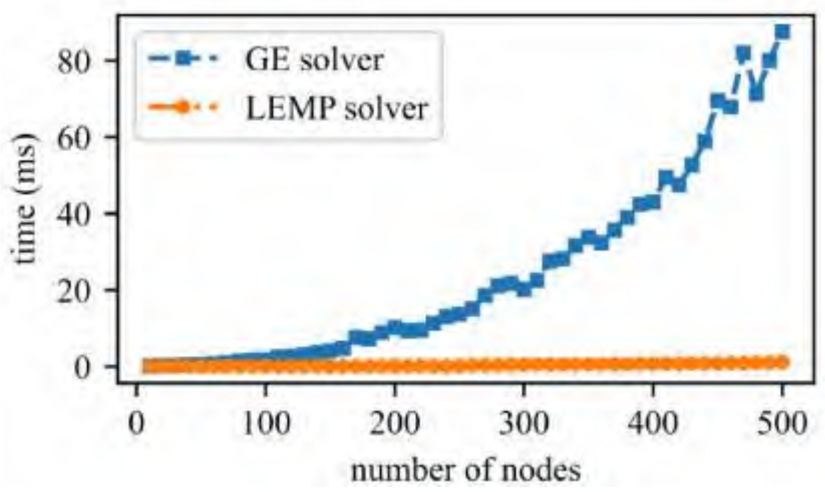


mean absolute error **iteration time** **algorithm performance space considering error and timing**

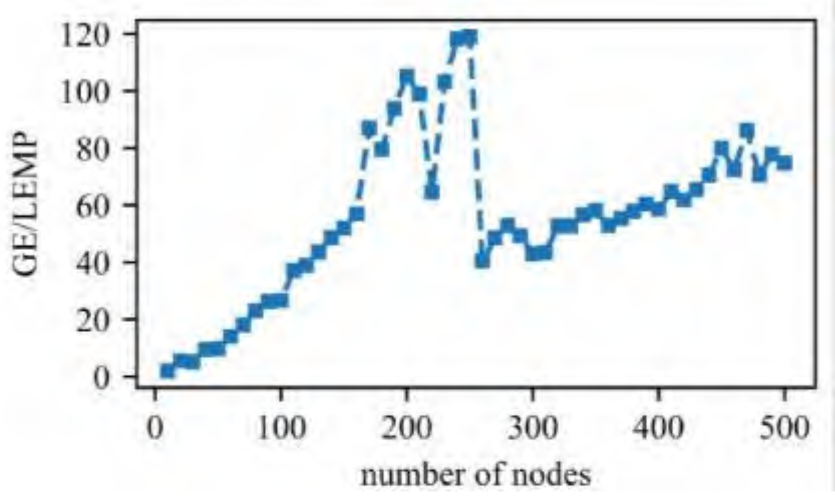
Memory challenges – Hardware/software Co-design



Algorithm Timing



Speed up Factor

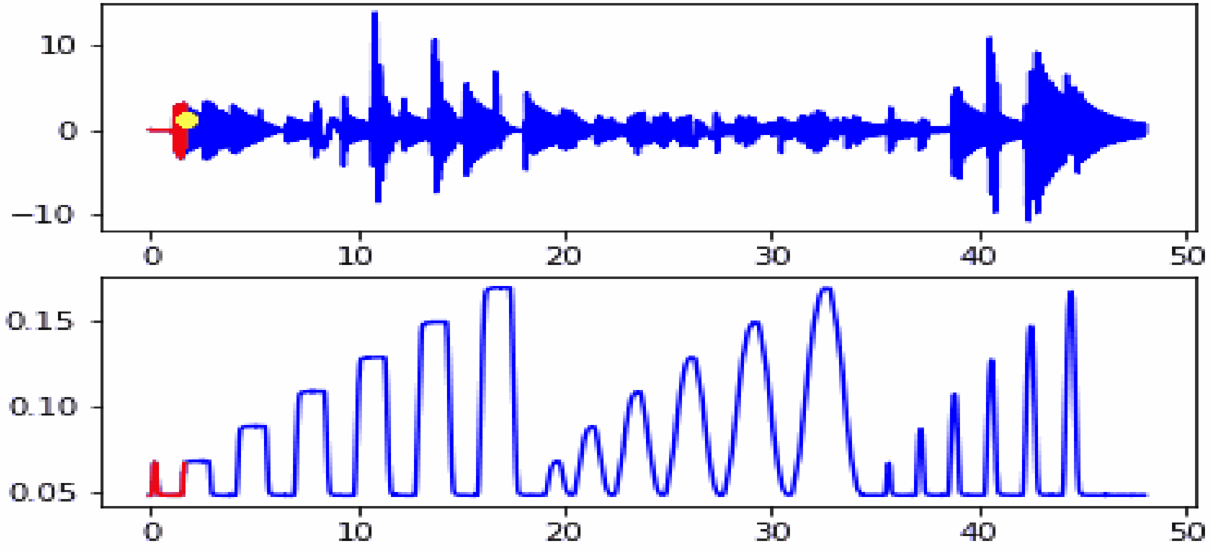


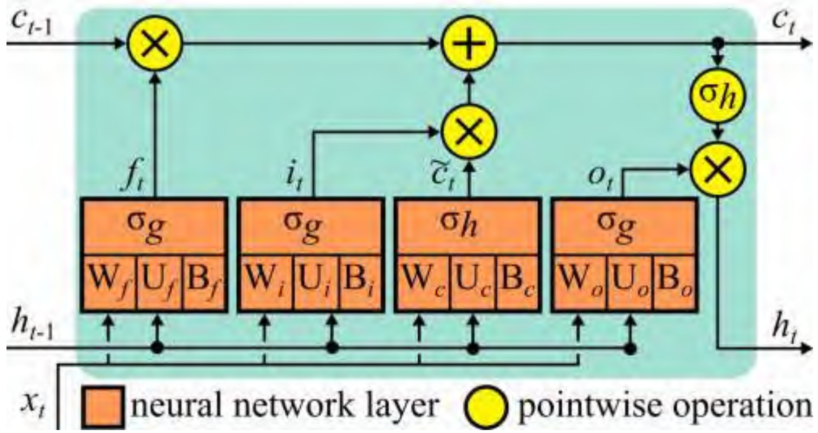
Data Driven Model Updating

LSTM-based Real-time State Estimation

In this work:

- Long short-term memory (LSTM) models are used for real-time state estimation.
- These data-driven models are trained offline on pre-recorded data.

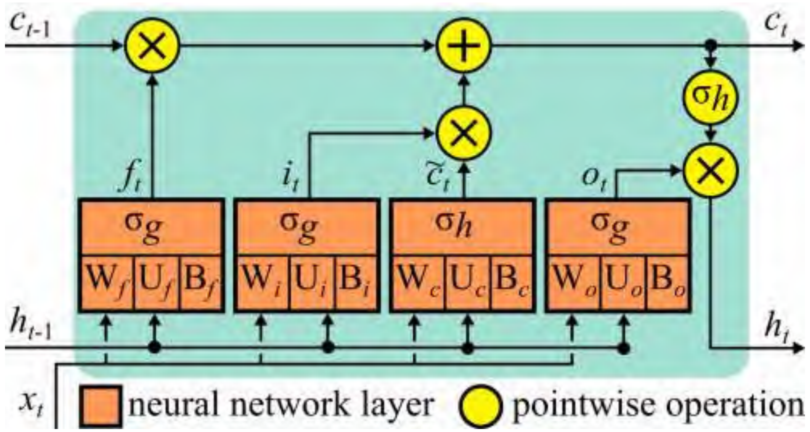


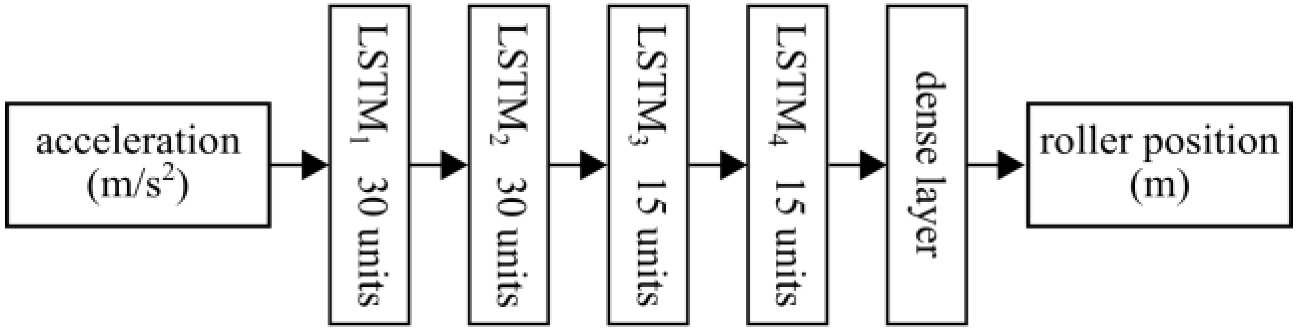


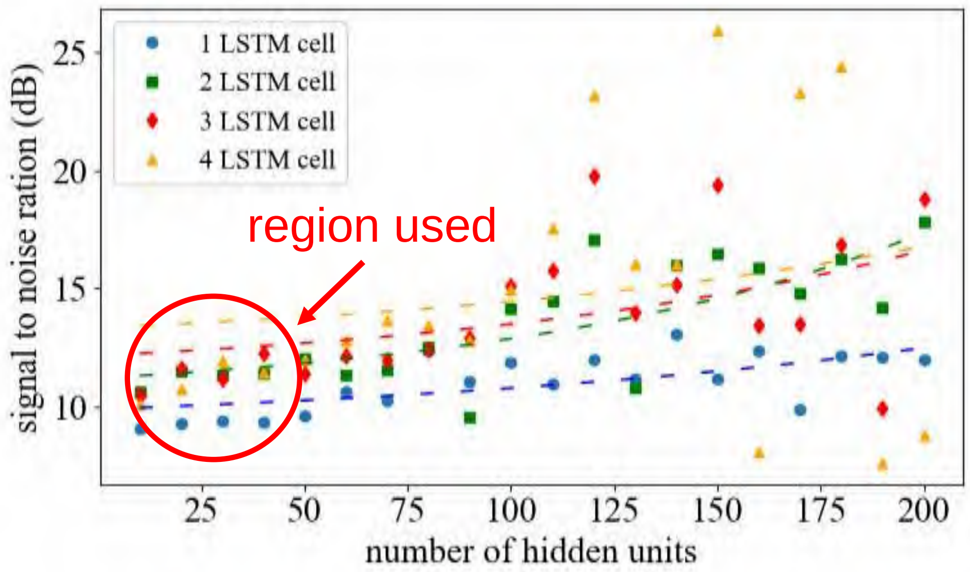
Long Short-term Memory Model

LSTM features and development:

- LSTMs are a Recurrent Neural Network (RNN) that propagates through long- and short-term memory forms.
- Four stacked LSTM cells (30, 30, 15, 15 units) with a fully connected layer at the output.







Model Deployment on a Real-Time Operating System (RTOS)

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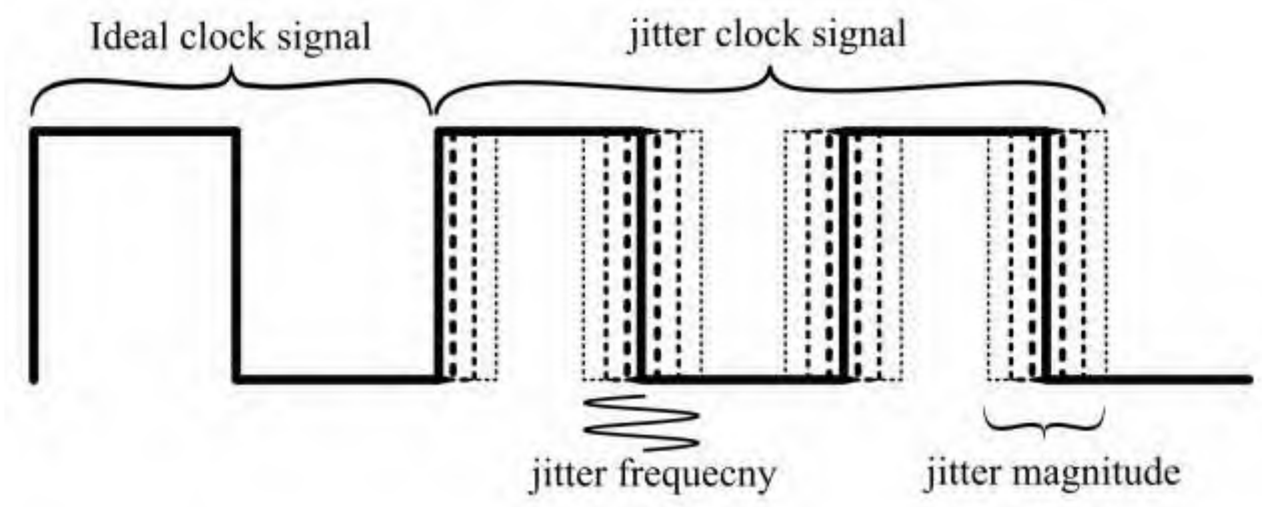
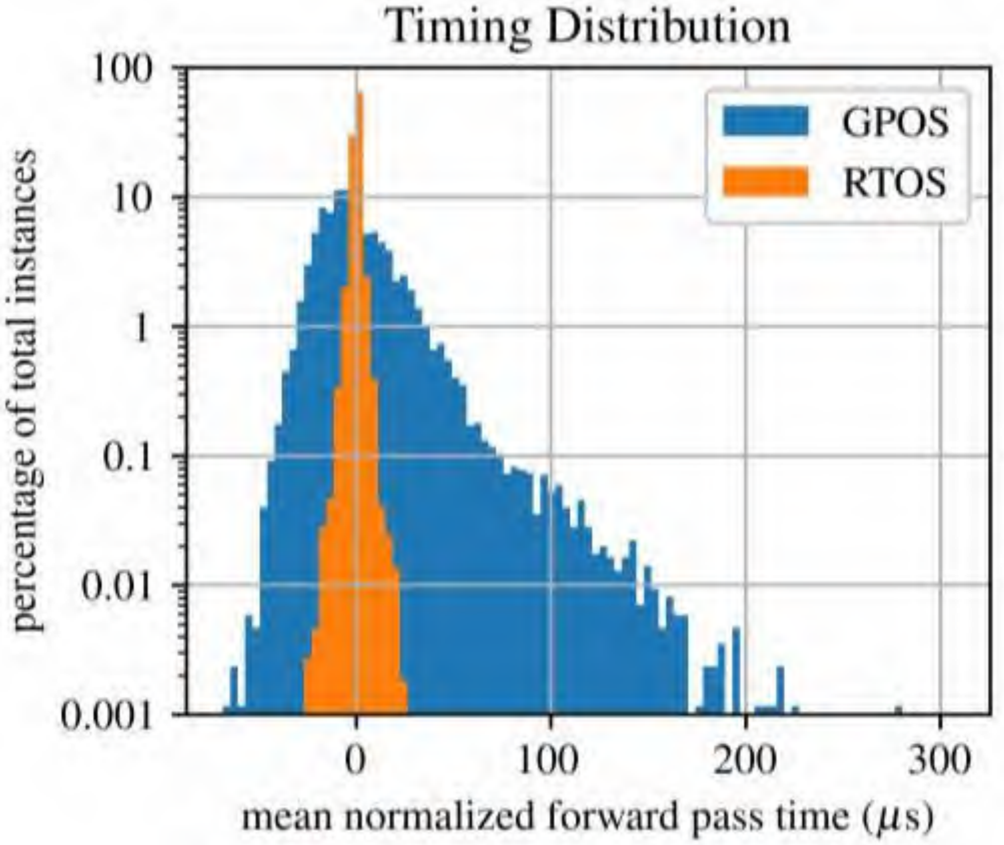
Real-Time Operating System (RTOS)

A real-time operating system (RTOS):

- Is an operating system for that processes data with defined time constraints.
- Is different from a time-sharing operating system which manages the sharing of system resources with a scheduler.
- Fully bounds timing constraints.
- Processes all data within time constraints.

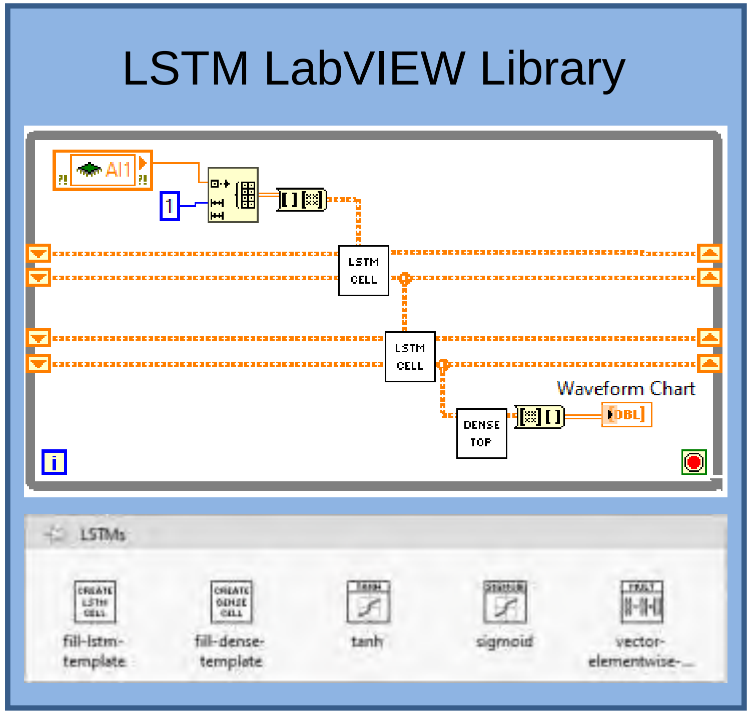


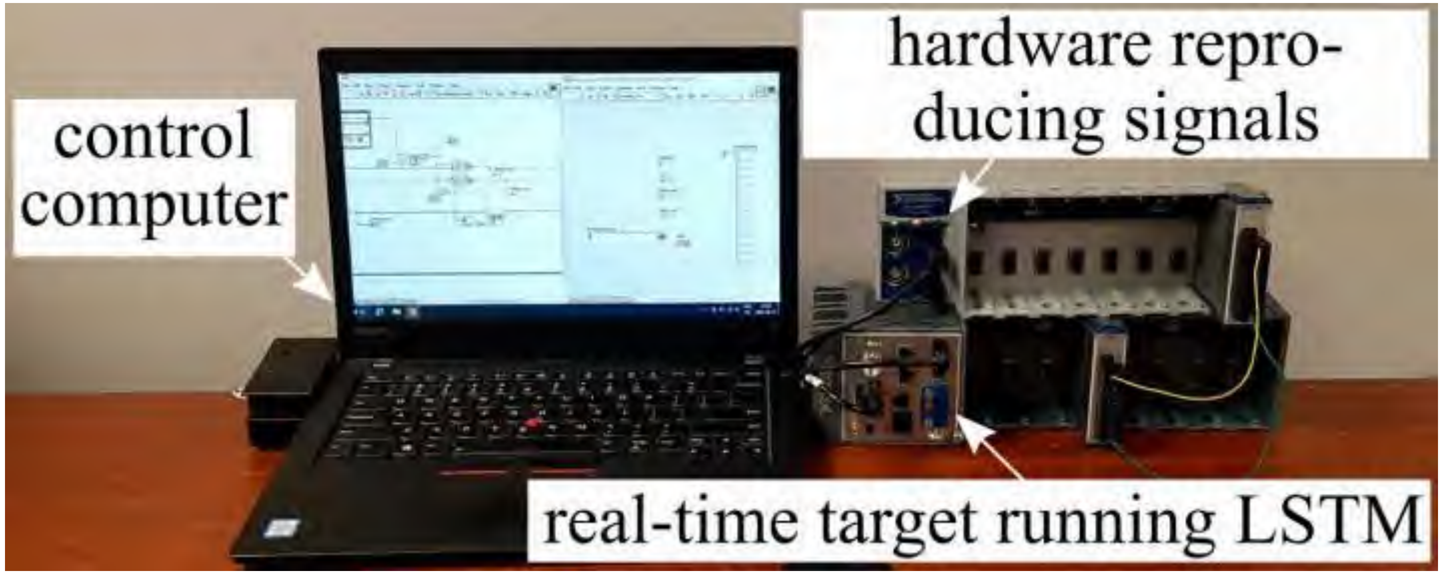


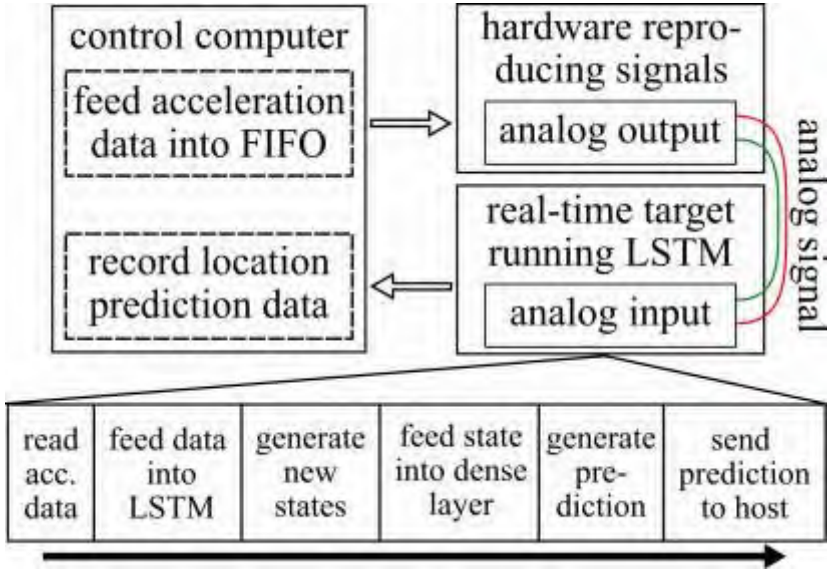
Model Deployment on RTOS

Real-time validation performed on an embedded system running:

- The experimental setup consisted of two subsystems:
  - **Hardware reproducing Signals** reproduces the dataset.
  - **Real-time Target re-**digitizes and feeds the input into the LSTM.
- Data is sampled at 1250 S/s; a prediction is made every 800 µs.
- State predictions are returned via a FIFO buffer to PC.



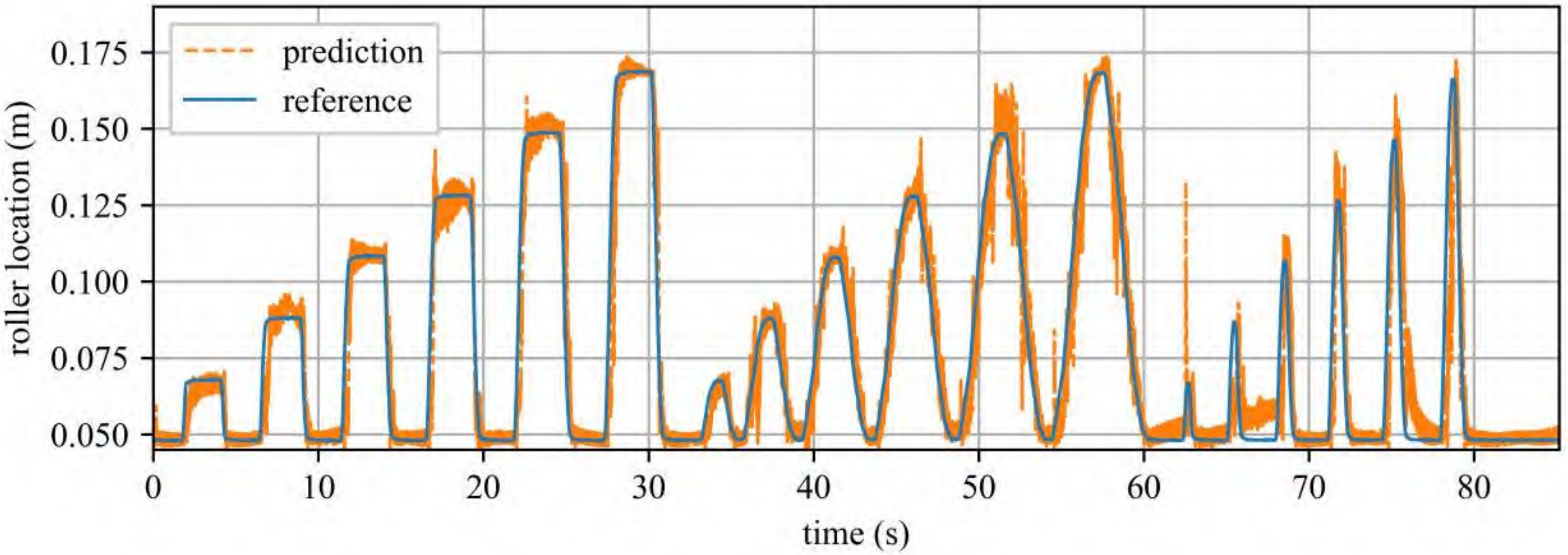




Real-time LSTM Modeling Results

LSTM model performance results:

- SNR_{dB} 17.4888 dB.
- RMSE of 11.471 m mm.
- LSTM traces reference pin location closely.



Real-time LSTM Modeling Results

LSTM model timing results:

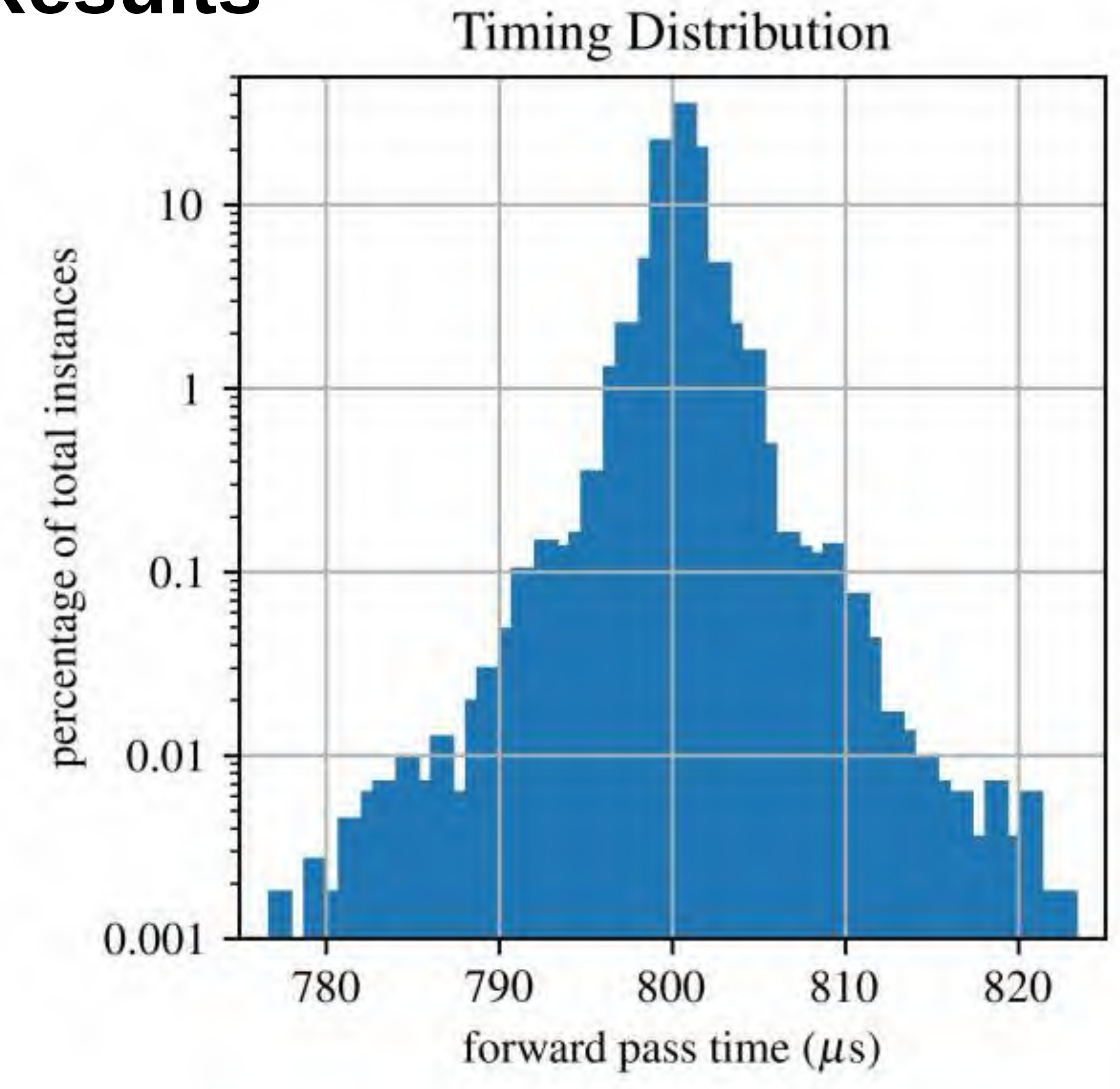
- Average: 800 µs.
- Standard deviation: 1.79 µs.
- Max overshoot: 26 µs.

Timing accuracy results:

- Execution-time jitter as expected.
- Timing follows a normal distribution.

Intel Atom® Processor E3825

- Total Cores: 2 (2 threads)
- Processor Base Frequency: 1.33 GHz
- Cache: 1 MB L2 Cache
- Use Conditions: Automotive, Embedded



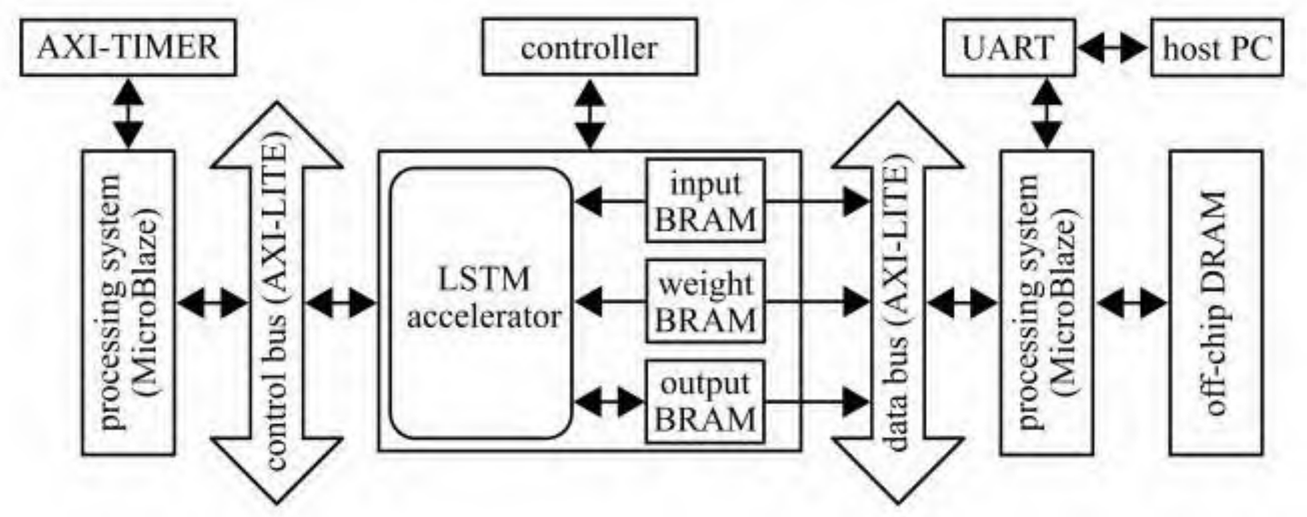
Model Deployment on a Field Programable Gate Array (FPGA)

South Carolina

Model Deployment on FPGA

LSTM model deployed on a Xilinx Virtex 7 (VC707) FPGA:

- Implemented in both 16-bit fixed point.
- Developed an LSTM hardware accelerator where data in and out the FPGA is pre and post-processed with the MicroBlaze soft core processor.

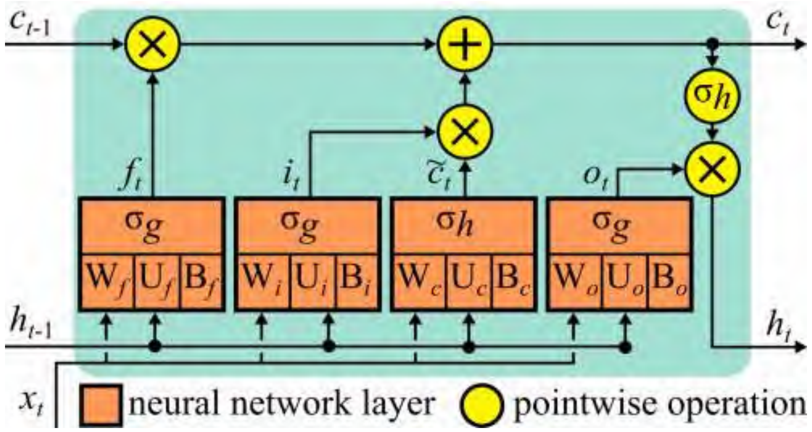


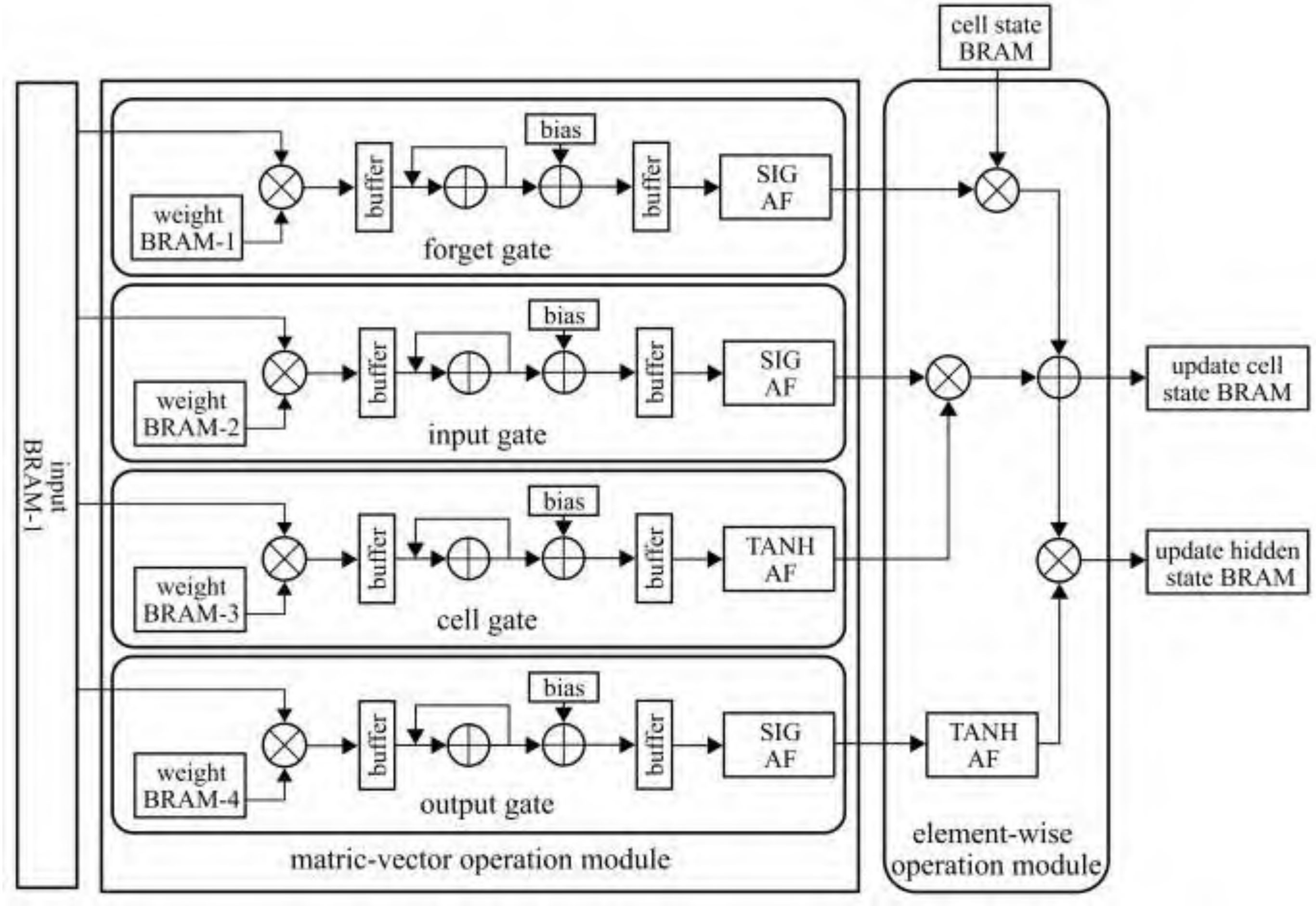
Xilinx Virtex 7 (VC707)

South Carolina

LSTM deployment on an FPGA

The developed hardware accelerator is split up into the LSTM's gates for deployment.

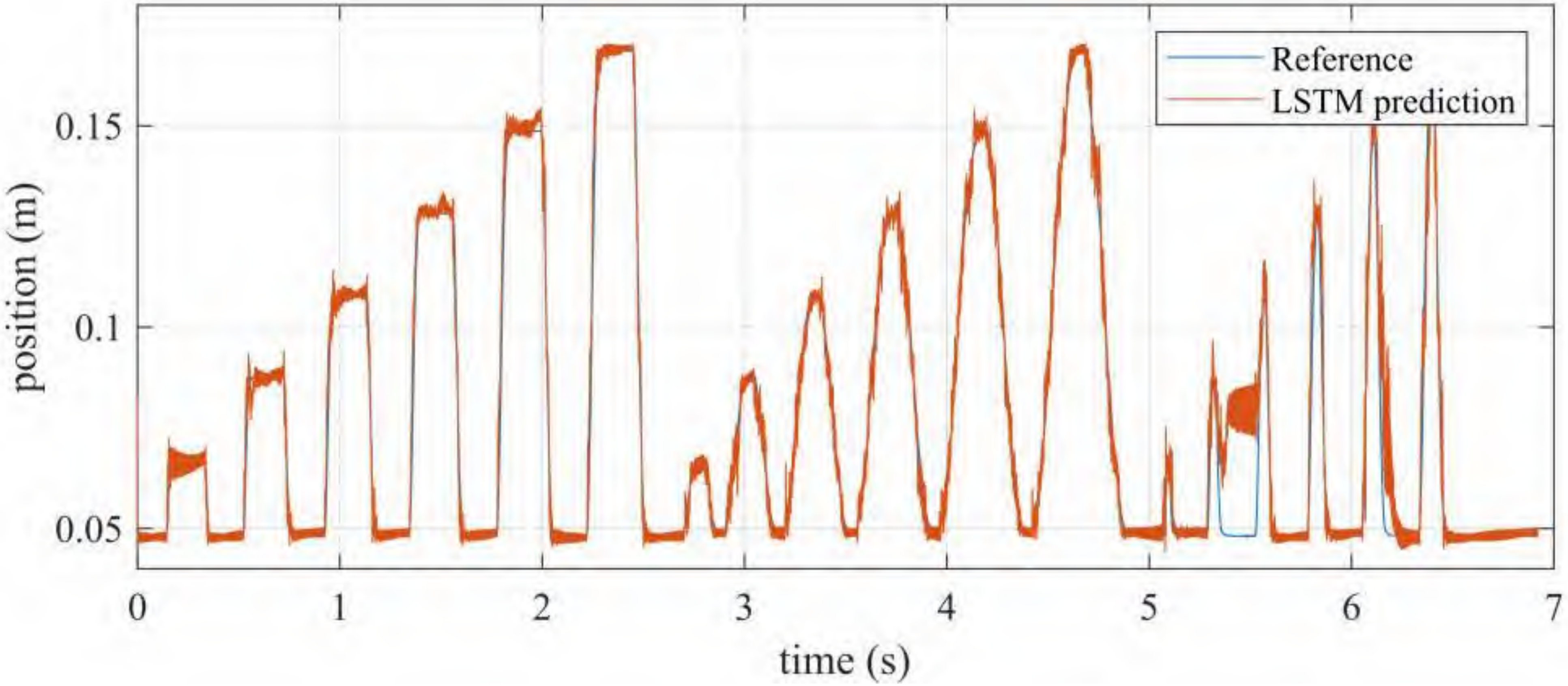




Real-time LSTM Modeling Results

16-bit fixed point model performance:

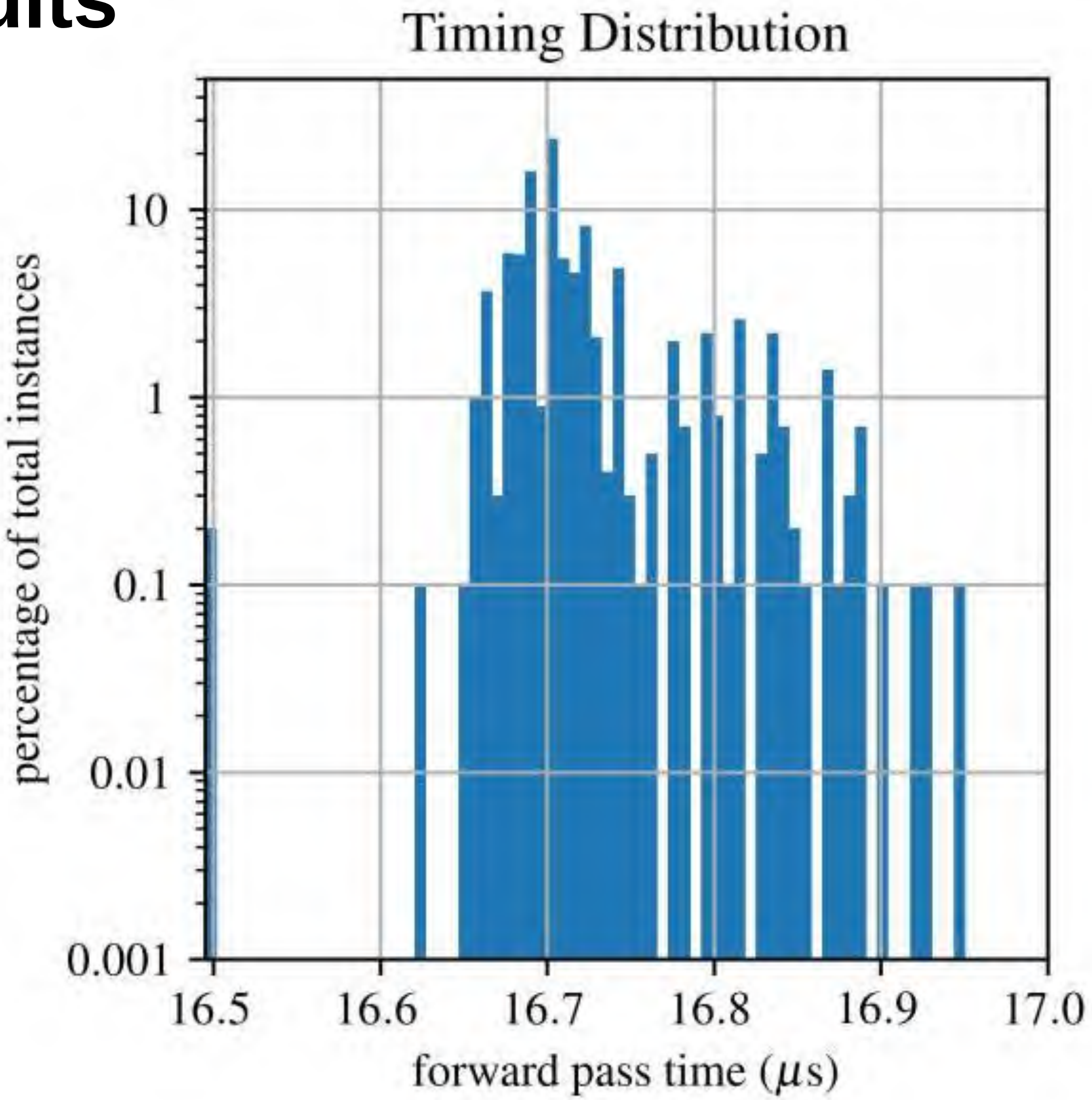
- SNR_{dB} of 19.54 dB.
- RMSE of 9.1 mm.



Real-time LSTM Timing Results

16-bit fixed point model performance:

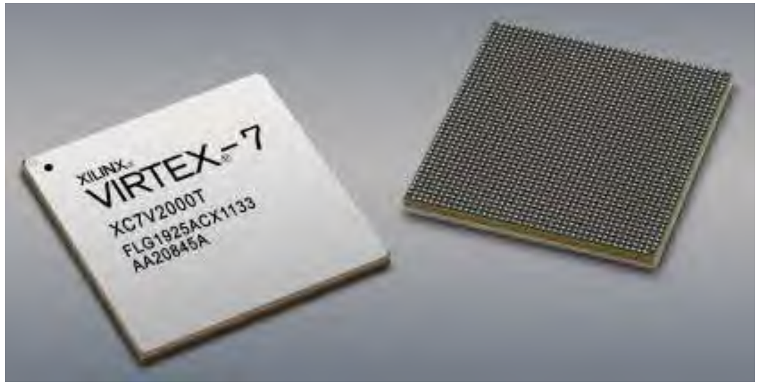
- Time step of 16.7 µs.
- Standard deviation: 0.0509 µs.
- 50X speed up over RTOS.



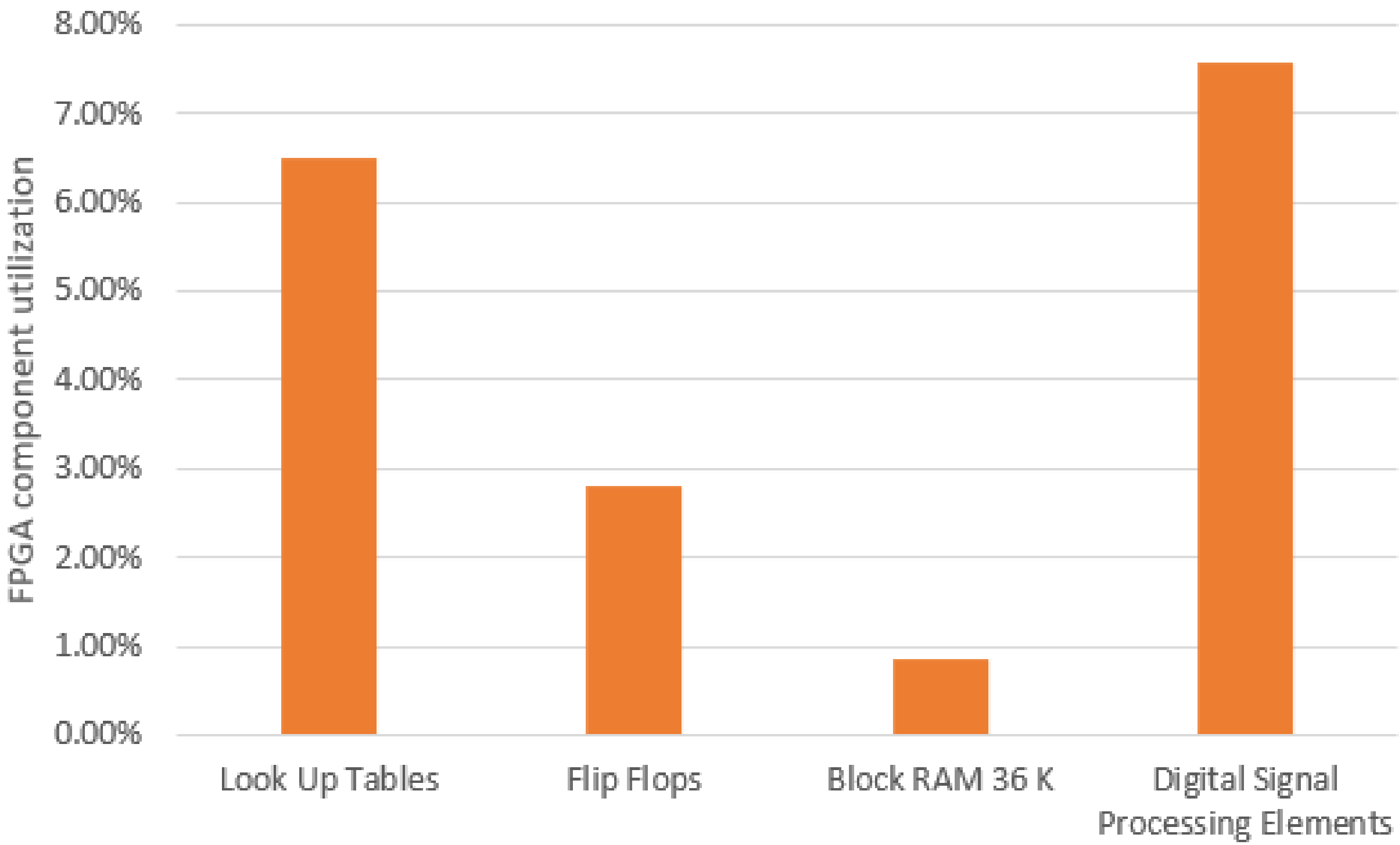
FPGA Resource Utilization Results

Synthesized for the Xilinx Virtex 7 (VC707):

- Consume less the 10% of FPGA resources.
- Has potential for deployment to much smaller FPGAs



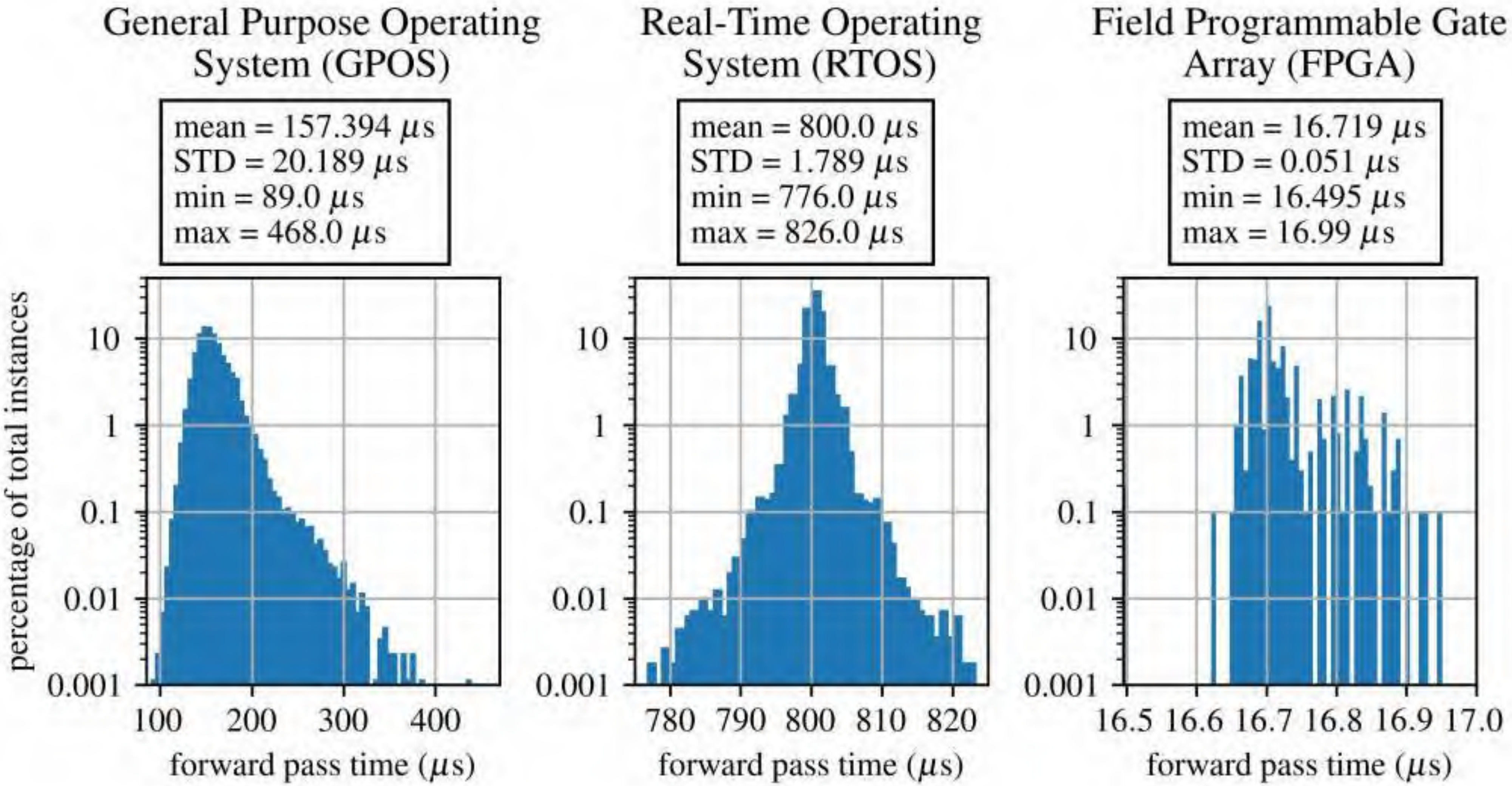
https://www.eetimes.com/new-xilinx-virtex-7-2000t-fpga-provides-equivalent-of-20-million-asic-gates/



Look Up Tables	Flip Flops	Block RAM 36 K	Digital Signal Processing Elements
126633	109186	229	212

GPOS vs RTOS vs FPGA

Timing characteristics by hardware implementation



DISCUSSION

Open-Source Codes and Data Sets

- LEMP solver: https://github.com/ARTS-Laboratory/Paper-Real-time-Structural-Model-Updating-using-Local-Eigenvalue-Modification-Procedure
- Secular equation solver: https://github.com/ARTS-Laboratory/Paper-Development-of-a-Real-time-solver-for-the-Local-Eigenvalue-Modification-Procedure
- DROPBEAR dataset: https://github.com/High-Rate-SHM-Working-Group/Dataset-2-DROPBEAR-Acceleration-vs-Roller-Displacement
- Open-Source library for Deploying LSTMs to the NI Linux Real-time Operating System at: https://github.com/ARTS-Laboratory/LabVIEW-LSTM

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Github-Lab: https://github.com/Arts-laboratory/

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