ONLINE IMPLEMENTATION OF THE LOCAL EIGENVALUE MODIFICATION PROCEDURE FOR HIGH-RATE MODEL ASSIMILATION

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HIGH-RATE STRUCTURAL HEALTH MONITORING

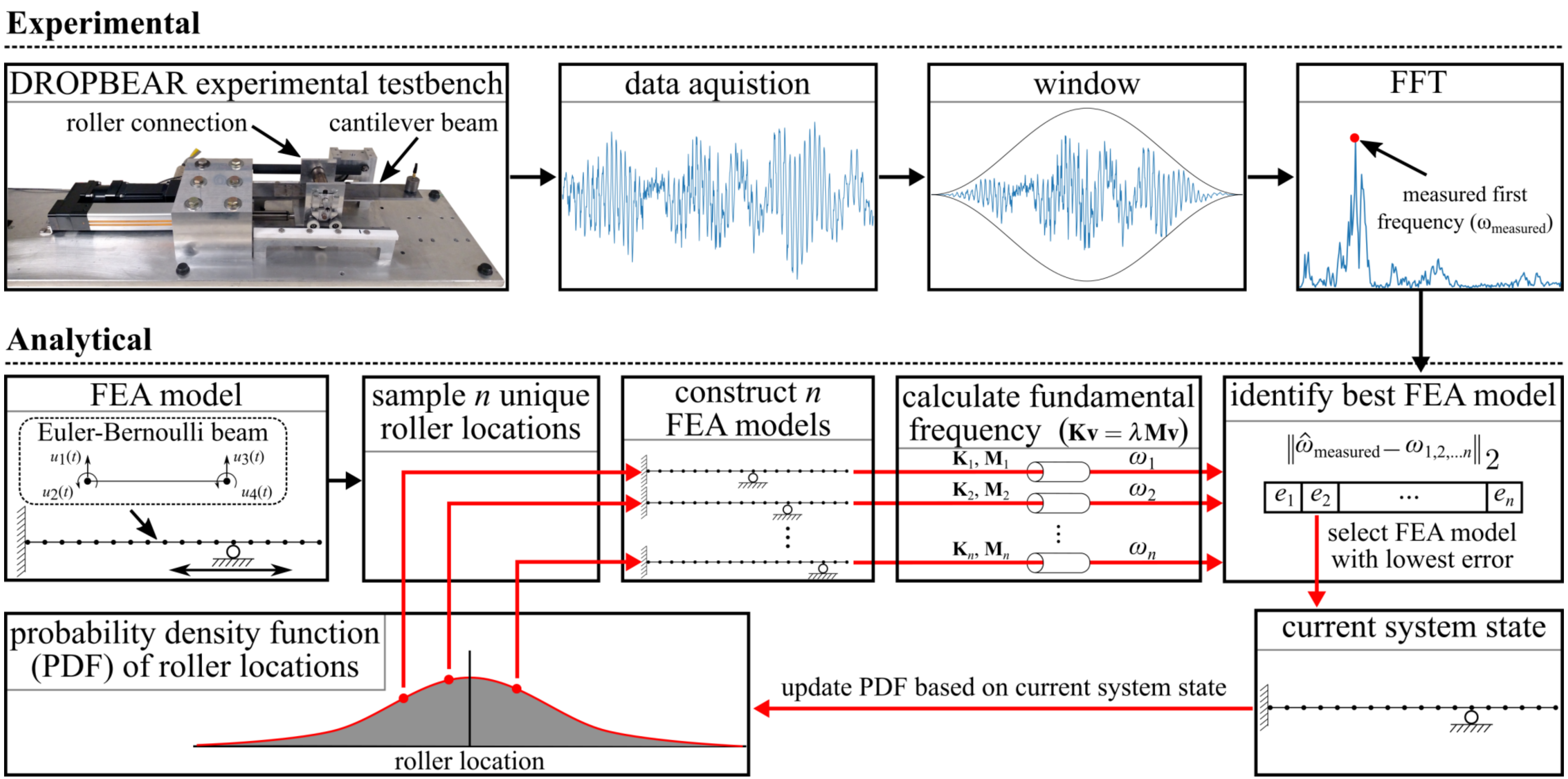
- Health monitoring of structures operating in high-rate dynamic environments behavioral interventions in response external stimuli.
- Examples of structures operating in high-rate dynamic environments include:
  - hypersonic vehicles
  - space craft
  - ballistic packages
- Intelligent reactions require an up-to-date model of the structure's state.

HIGH-RATE STRUCTURAL HEALTH MONITORING

- Due to the timescale of relevance to these structures means that the model must be continuously updated with a time step of 1 millisecond or less.
- However, traditional frequency-based methods for updating the finite element model online require solving the generalized eigenvalue problem a computationally expensive process.

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

WHY A LIVE MODEL UPDATE

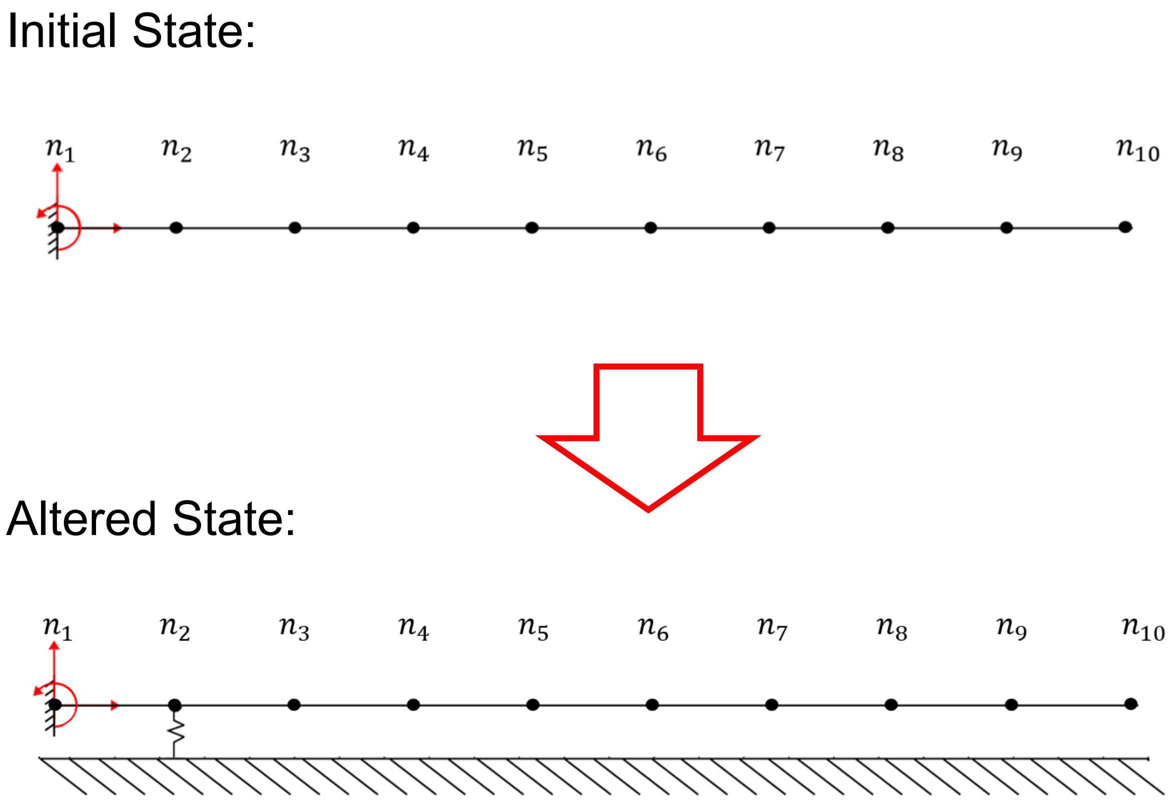
- The logical consideration is that solving for the position at all will always be slower than a look up table
- Model Updating holds promise for:
  - 2D systems such as thin plates
  - Multiple sequential modifications such as crack progation or multi damage sources
- The look up table would grow impractically large as the dimensionality of the problem increases as pre-calculated solutions are required every potential case and its branching evolutions

LEMP

- The Local Eigenvalue Modification Procedure (LEMP) is put forward to accelerate the extraction of natural frequencies from finite element models updated online.
- LEMP:
  1. presolve for the eigenvalue solution to a reference state of the system
  2. computes the single (i.e., local) change in the modal domain from the reference state to the current state online. The modal domain update in the local eigenvalue modification procedure bypasses the general eigenvalue problem, which is the most expensive computational step.

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.



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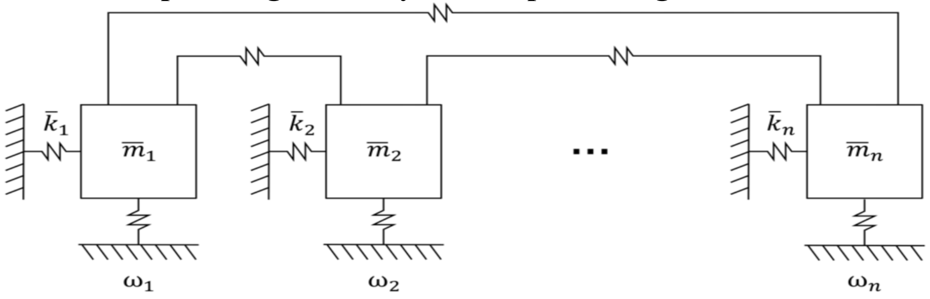
Local Eigenvalue Modification Procedure (LEMP)

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

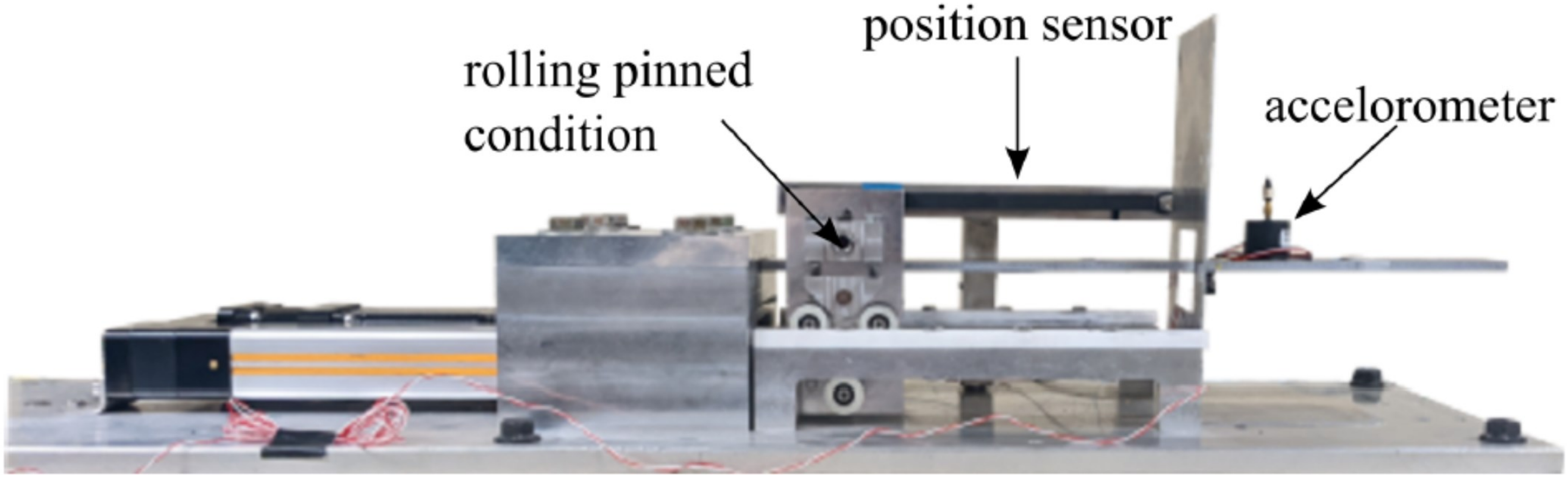
$$\frac{-1}{\alpha} = \sum_{r=1}^{m} \frac{v_r^2}{\omega_r^2 - \Omega_r^2}$$

Solved using Divide and Conquer method

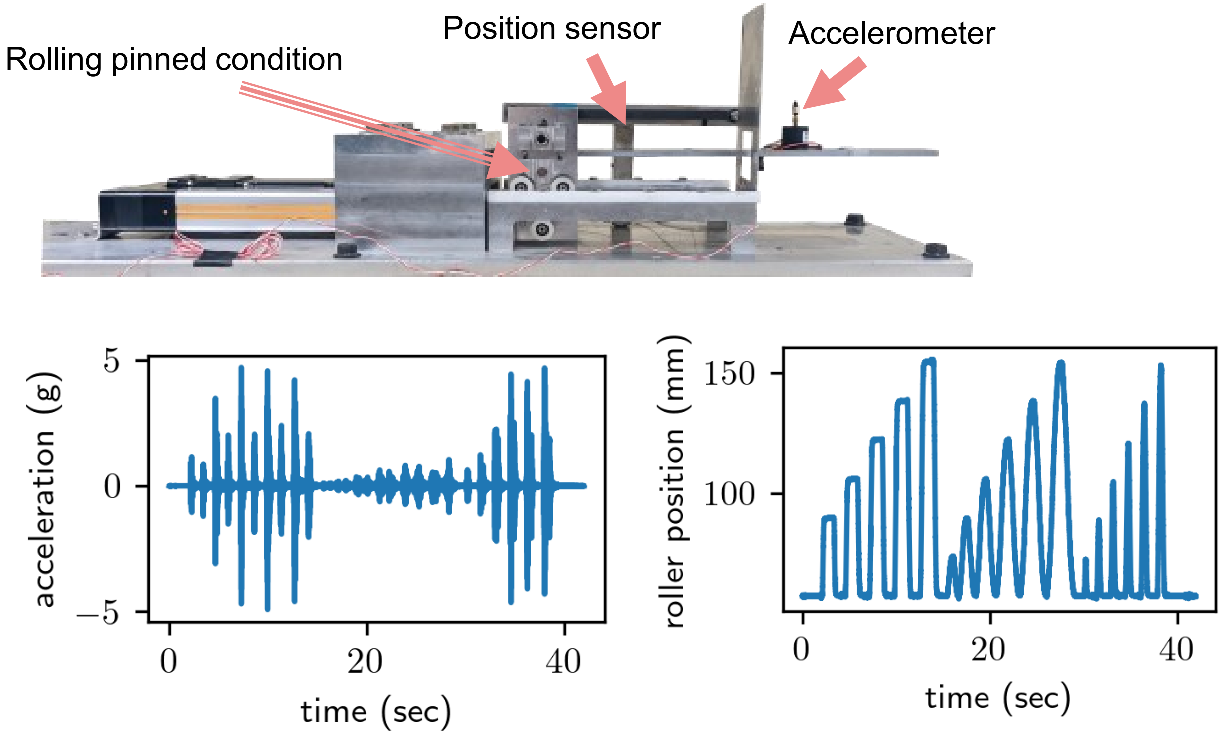
Avitabile, P., "*Twenty Years of Structural Dynamic Modification- A Review*," *Sound and Vibration*, pp. 14-25. 2003
Drnek, C. R., "*Local eigenvalue modification procedure for real-time model updating of structures experiencing high-rate dynamic events*," (2020).

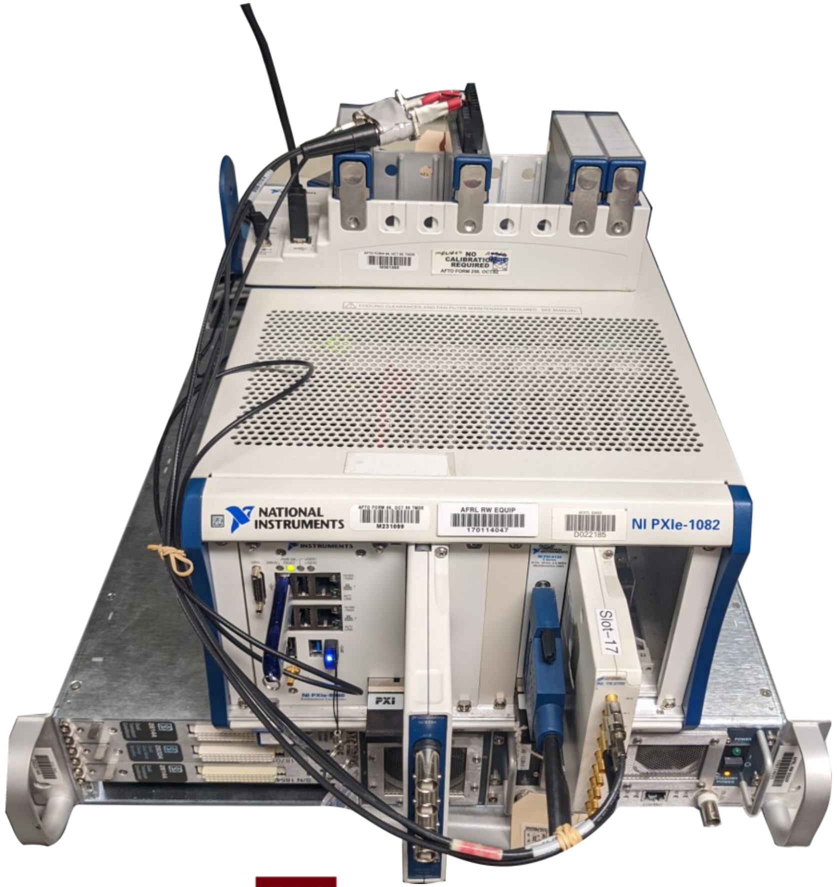
DROPBEAR

- Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research (DROPBEAR) testbed



CYBER PHYSICAL EQUIVALENT





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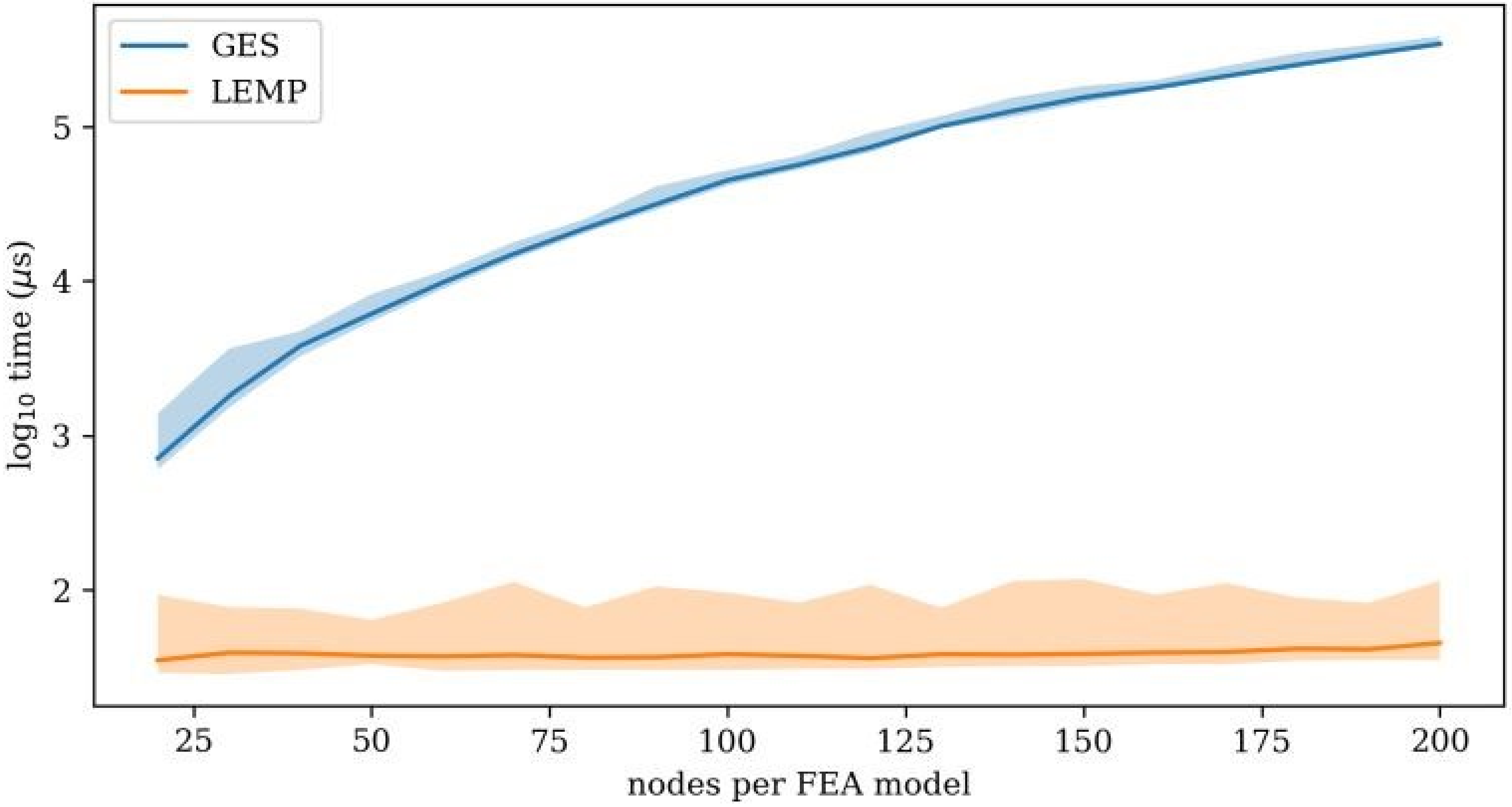
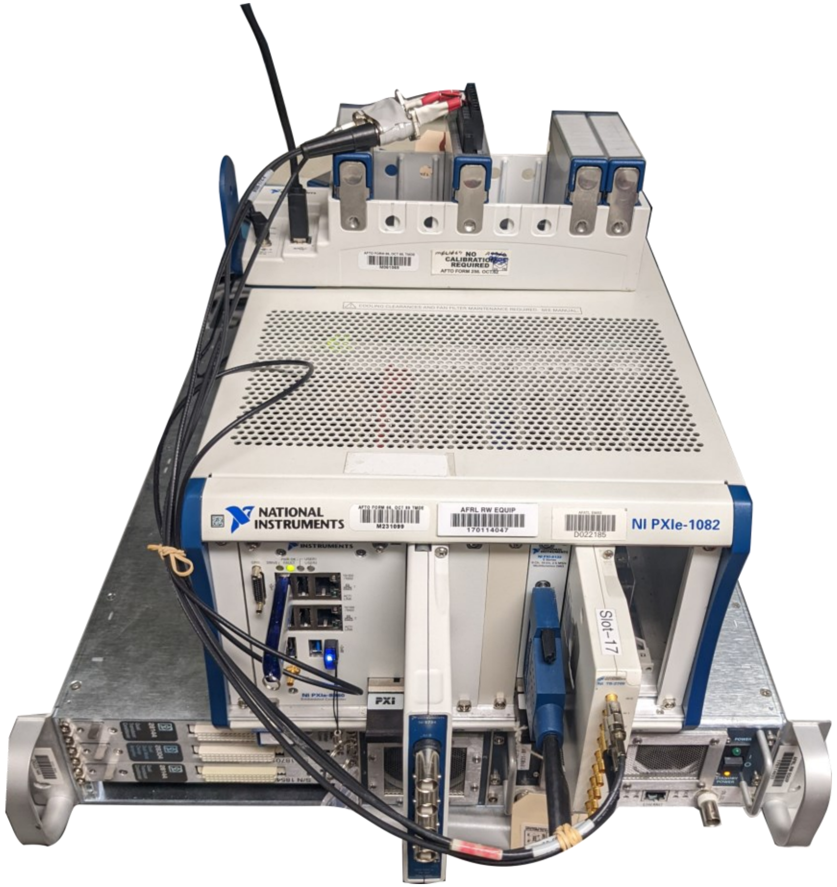
AGLORITHMIC TIMING TARGETS





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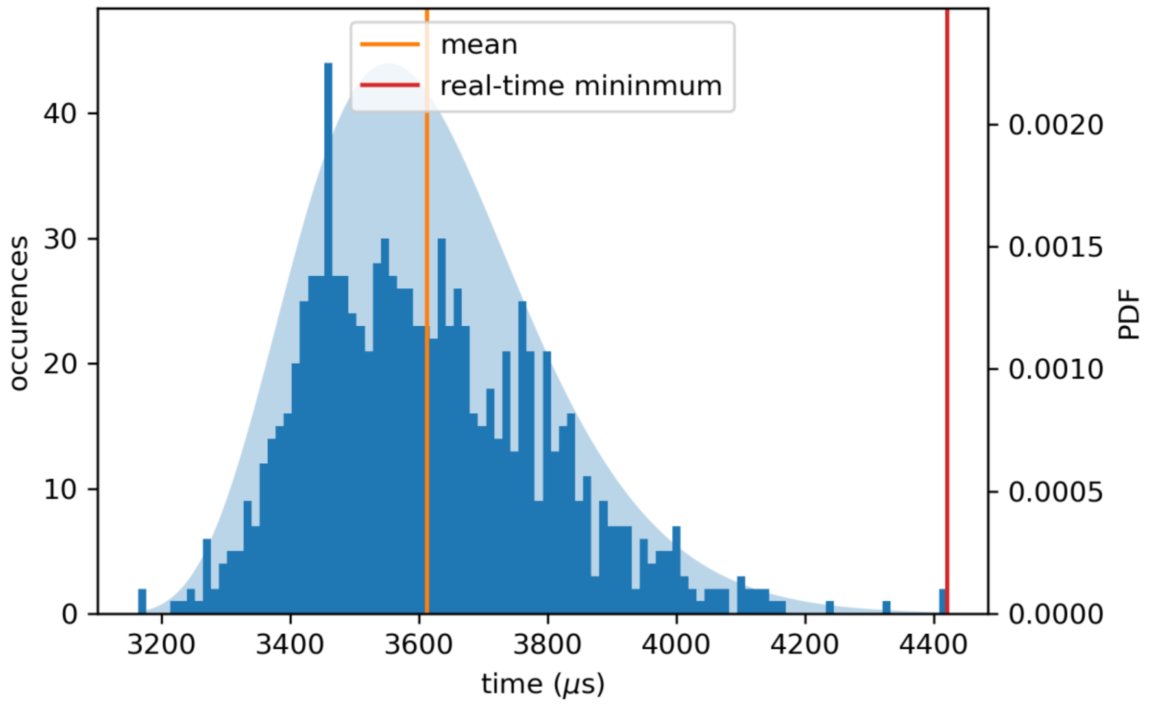
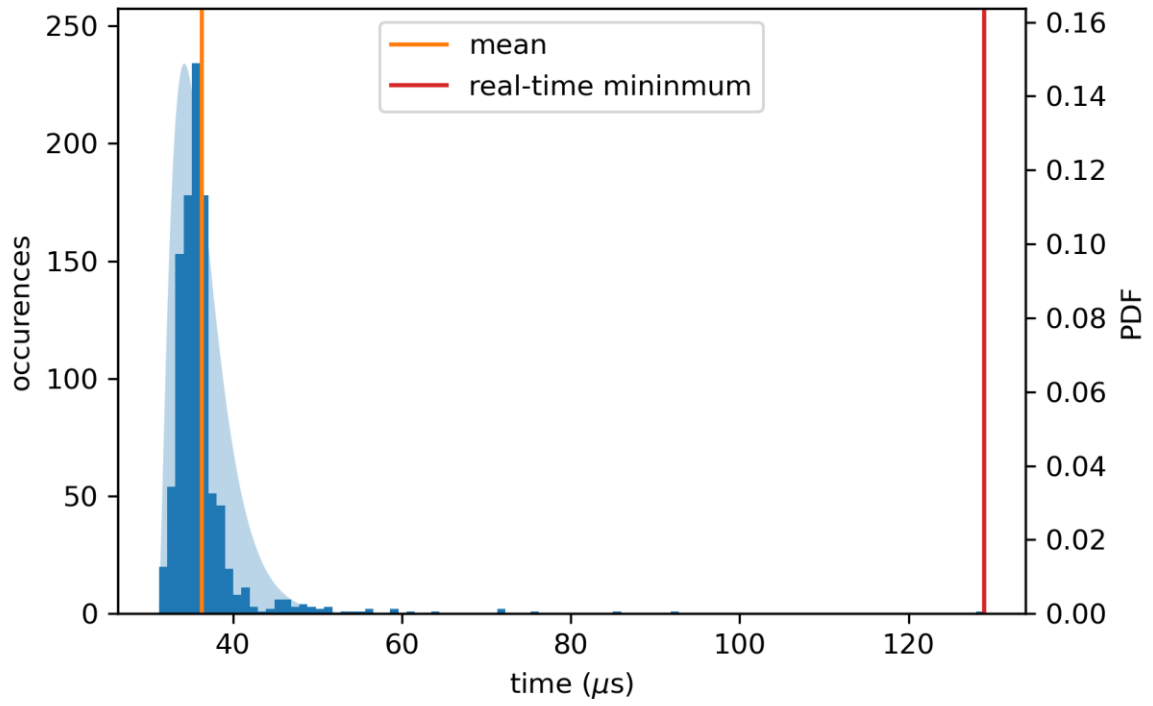
PERFORMANCE: TIMING OUTSIDE THE LOOP

General Eigenvalue Solver



Local Eigenvalue Modification Procedure



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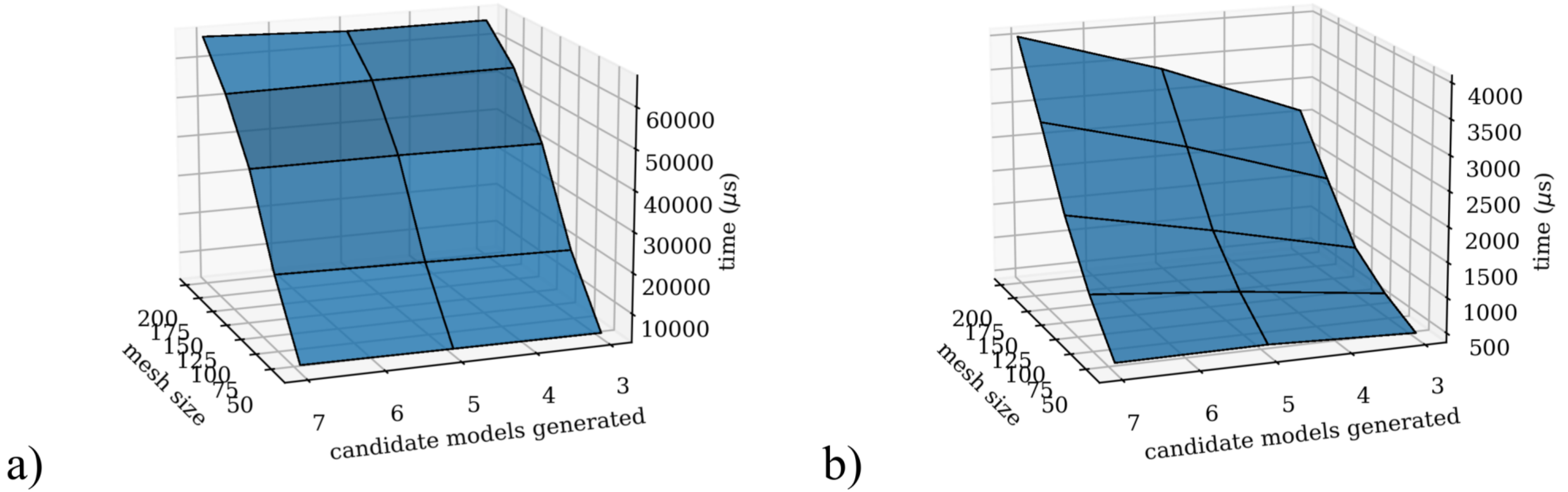
PERFORMANCE: TIMING OUTSIDE THE LOOP

Nodes	LEMP (µs)	NES (µs)	CF (µs)	GES (µs)
40	38.90	2,283	2,916	3,804
120	36.16	26,491	41,137	73,593
200	45.39	89,066	153,671	344,519

PERFORMANCE WITH HARDWARE IN THE LOOP

Time for FEA execution versus nodes for a) GES and b) LEMP each using a FFT window of 5000 points (0.02 s).



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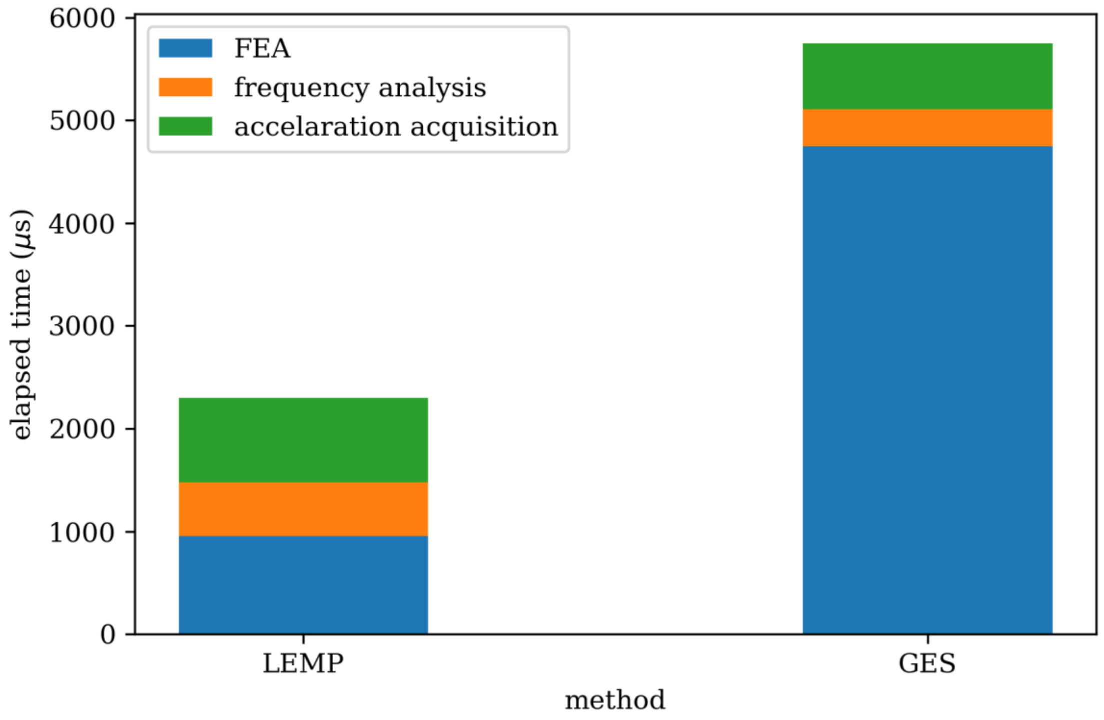
PERFORMANCE WITH HARDWARE IN THE LOOP

Time execution for Local Eigenvalue Modification Procedure (LEMP) vs a General Eigenvalue Solver (GES)



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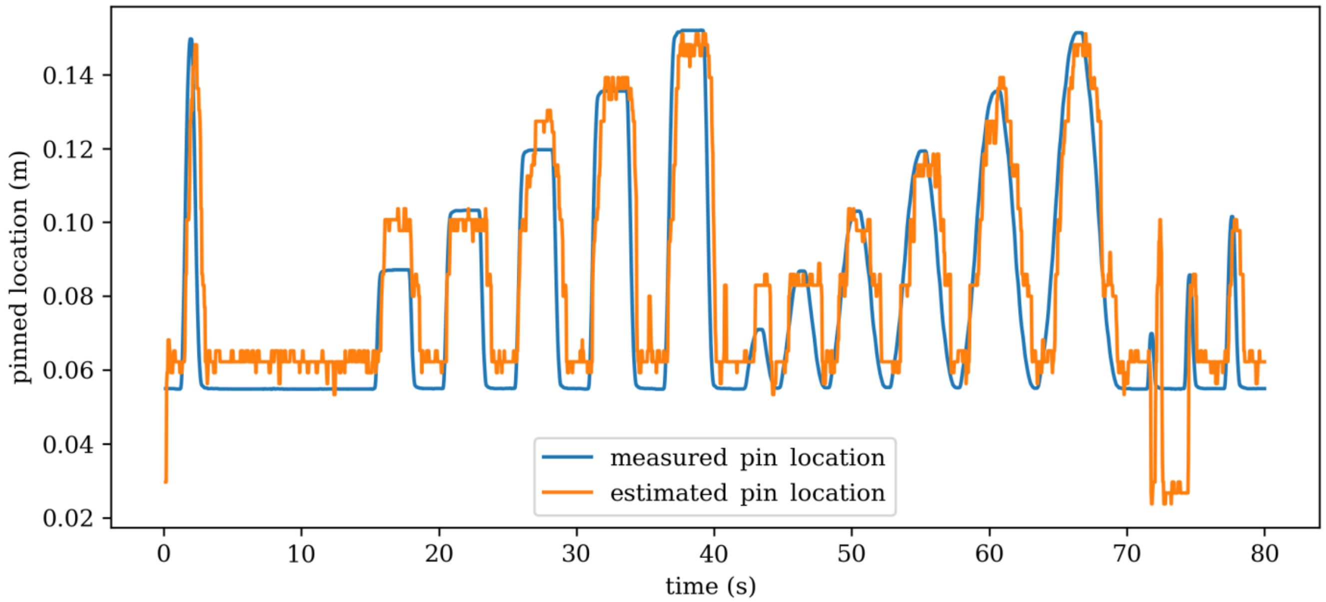
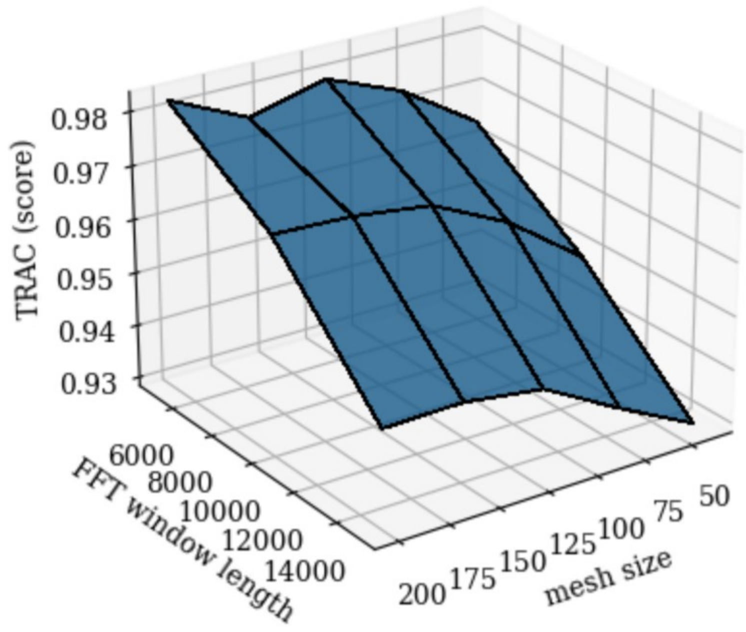
PERFORMANCE WITH HARDWARE IN THE LOOP

HIL position tracking implementation using LEMP with a mesh size of 120 nodes, testing 5 candidate models, and using a FFT window size of 5000 points (0.02 s).

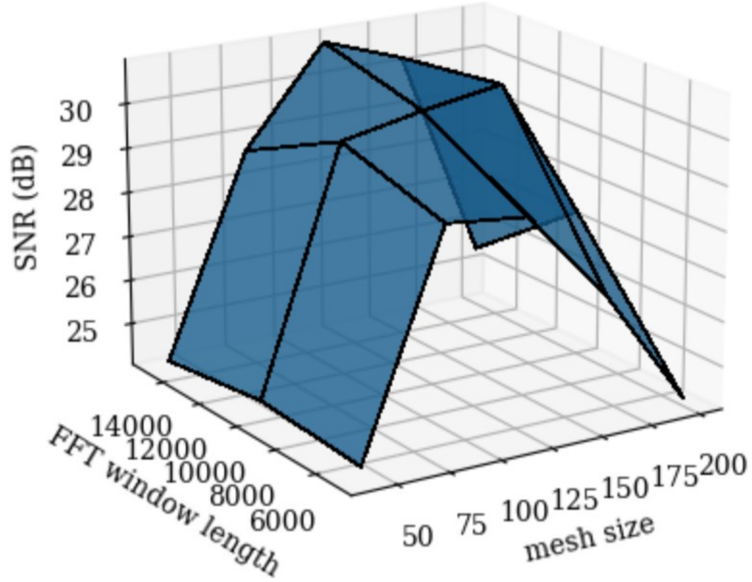


PERFORMANCE WITH HARDWARE IN THE LOOP

Performance metrics for HIL implementation shown in a) TRAC and b) the SNR of LEMP as a function of mesh size and FFT window length.



a)



b)

CONCLUSION

LEMP is demonstrated to accelerate the extraction of natural frequencies from finite element models updated online with real-time constraints on real-time hardware. LEMP's linear time cost makes it ideal for further extensions and studies into high-rate state estimations.

The LEMP algorithm has allowed a greater than a 10x reduction under ideal conditions in model update time, surpassing the 1 ms time target and reaching 1ms update time on live hardware.

FUTURE WORK

Live model update the methodology would be expanded to include two-dimensional analysis and sequential damage cases, emphasizing the need for intelligent model selection and outlier filtering.

ACKNOWLEDGEMENTS

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