METHODOLOGY FOR REAL-TIME STATE ESTIMATION AT UNOBSERVED LOCATIONS FOR STRUCTURES EXPERIENCING HIGH-RATE DYNAMICS

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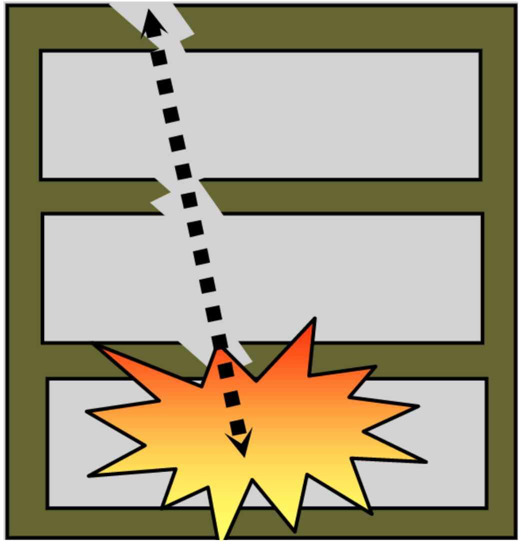

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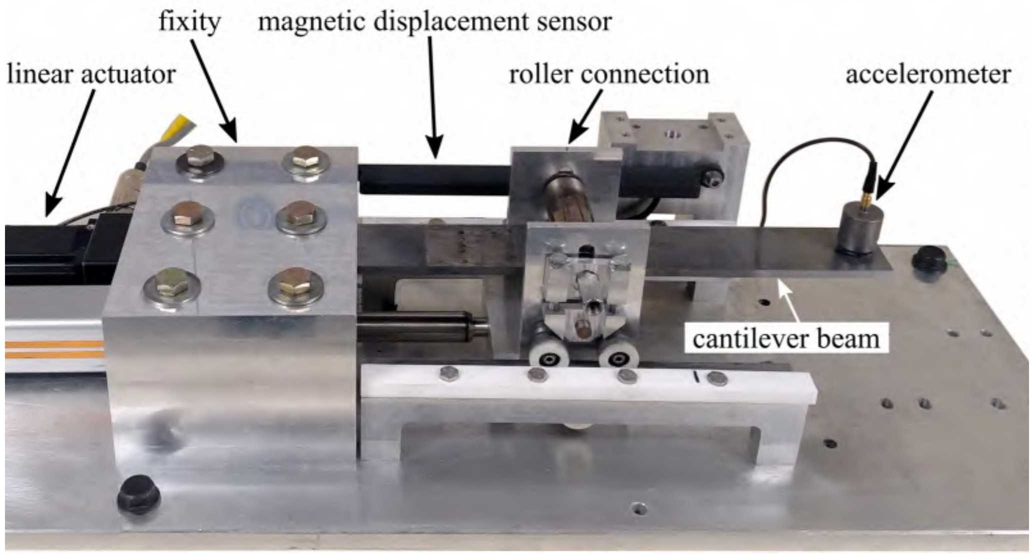

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Structures Experiencing High-Rate Dynamic Events

Ballistics Packages

Active Blast Mitigation

Hypersonic Vehicles

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Fuzes for Hard Targets

Harsh environment delicate payload

The Challenge of Hard Target Fuze Design

- Fuzes are a relatively delicate payload
- Fuzes break in harsh environments
- Too many failure modes for fly-fix-fly approach
- Full scale high-g testing is expensive
- Full scale high-g testing can't uncover all failure modes

Desired Outcomes

- Fuzes have one good outcome:
  - Initiation when intended
- They have two incorrect outcomes:
  - Initiation before or after intended
  - Failure to initiate

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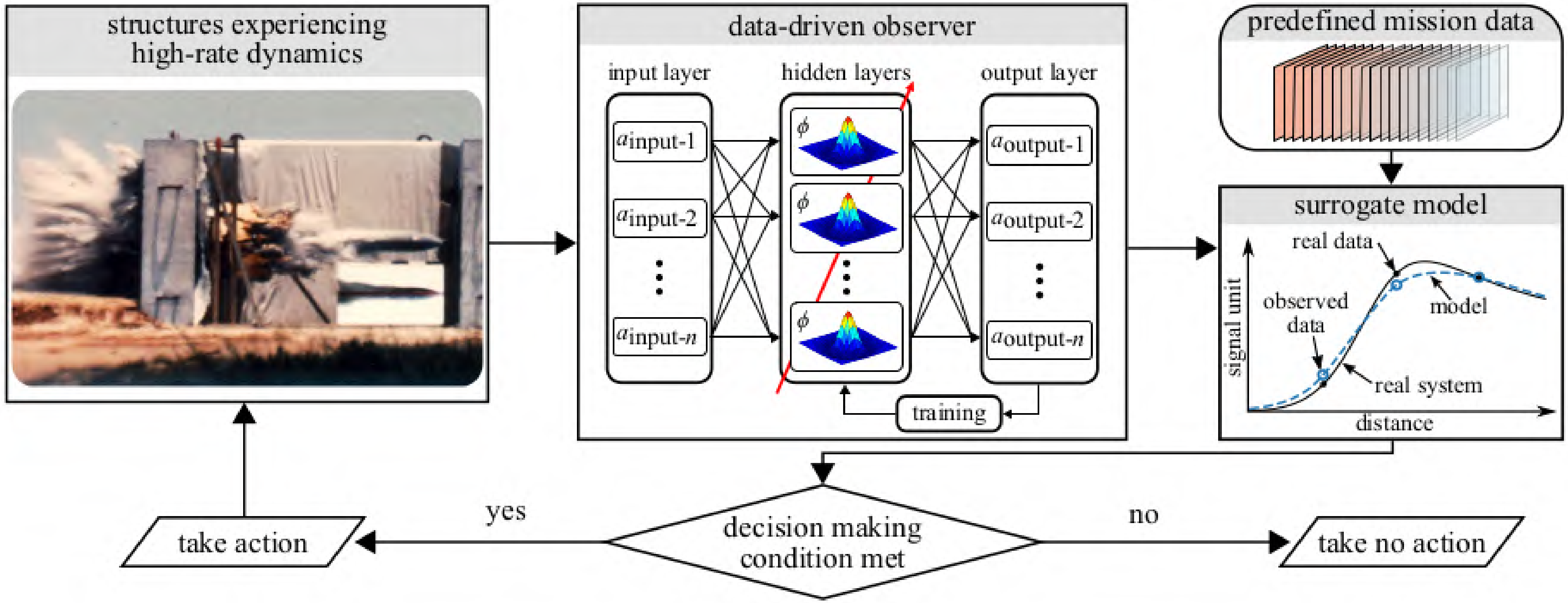
Goal: Real-Time Decision-Making for Structures Experiencing High-Rate Dynamics

Real-time decision making requires the development of two key enabling technologies:

1) low-latency (2 ms) model updating; and

2) near-time prognostics of the system state.



Challenges Related to Computing on the Edge

In the development of solutions for this problem we are operating within the following constraints:

- Computational power at the edge is limited. This includes memory, processors, and available energy.
- The system is too complex to pre-calculate a library of existing fault cases.
- The inputs (forces, location) will never be known.
- Rare and extreme events will happen and must be accounted for.

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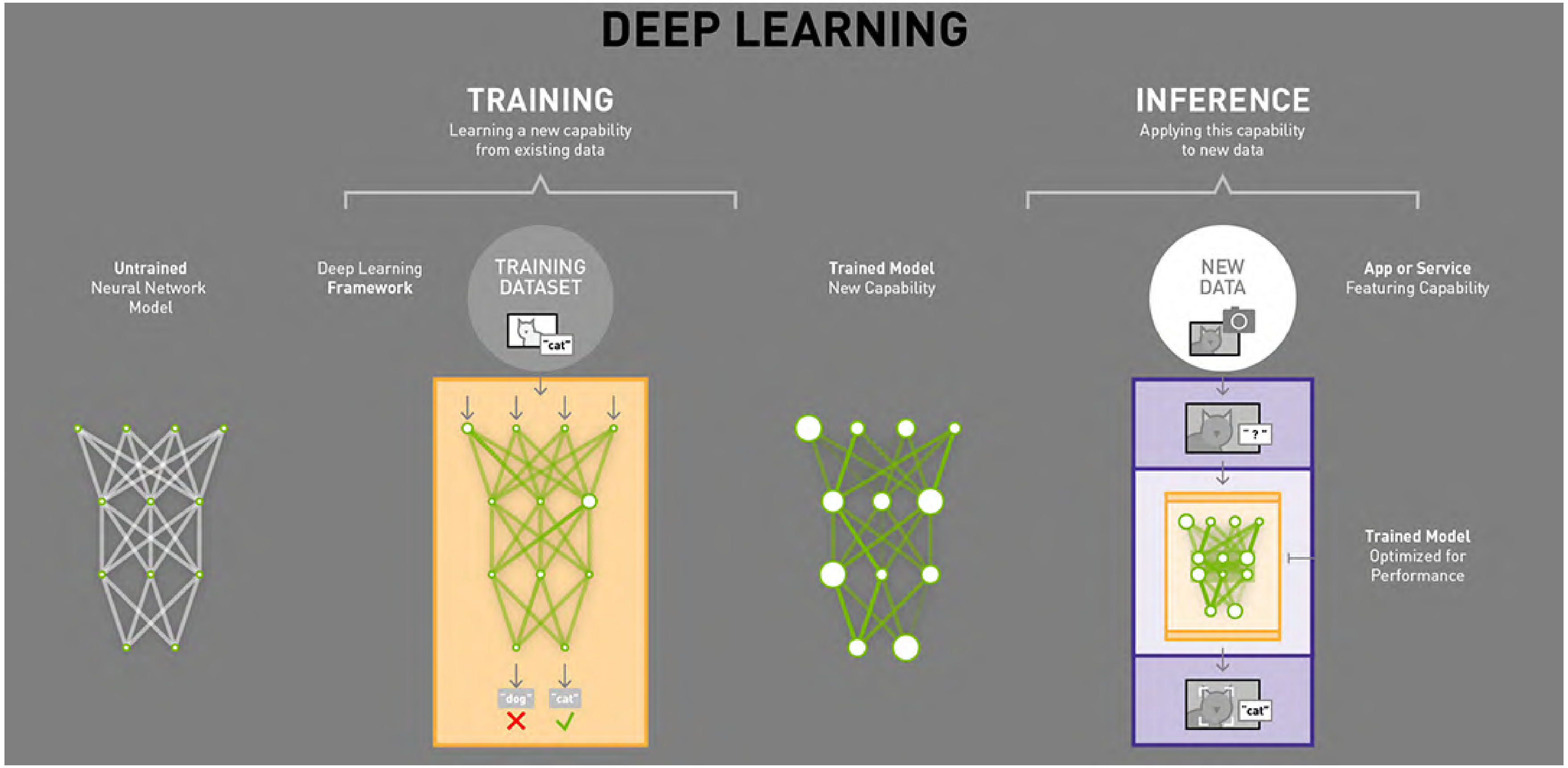
Research Endeavor 1: Real-Time Training of an Artificial Neural Network

Background: Machine Learning, Training Vs. Inference

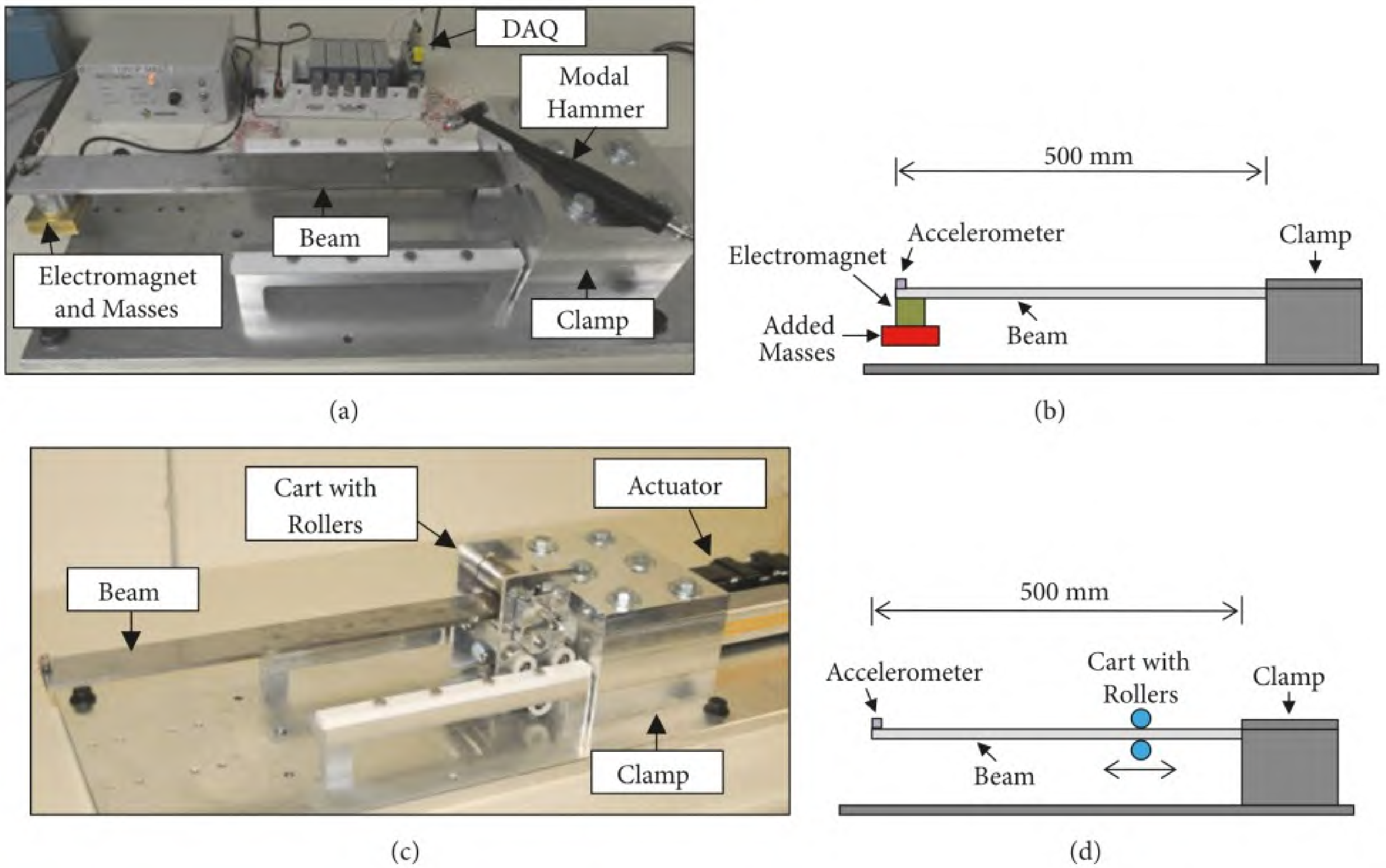
Inference is where capabilities learned during training are put to work:

- Training: Learning a new capability from existing data.
- Inference: Applying this capability to new data.



nvidia.com/blog/2016/08/22/difference-deep-learning-training-inference-ai/

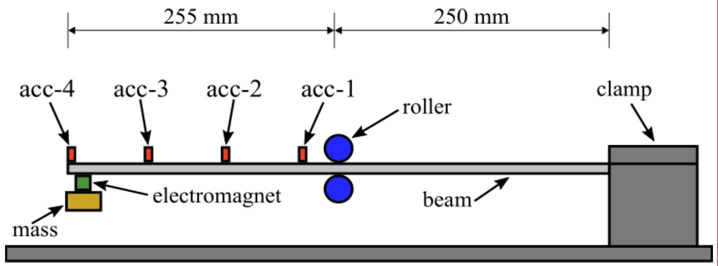
DROPBEAR (Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research)

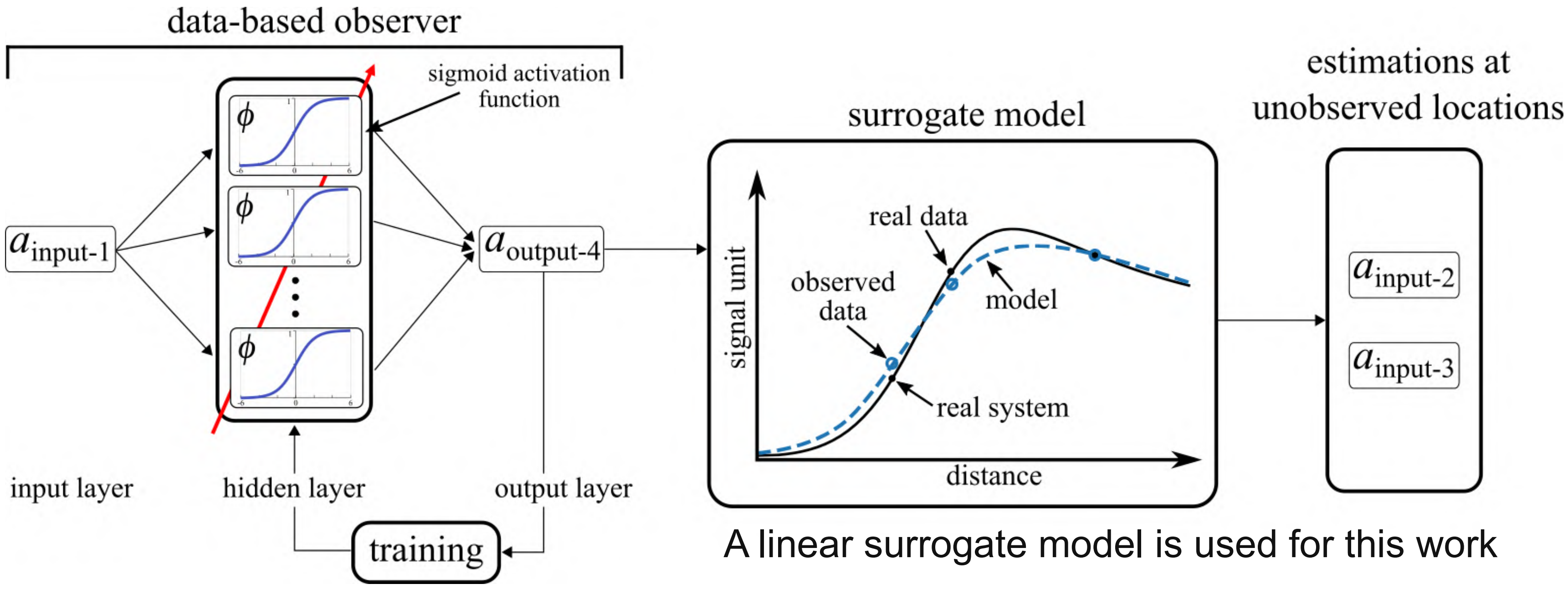


Real-Time Training of a Feed Forward Neural Network

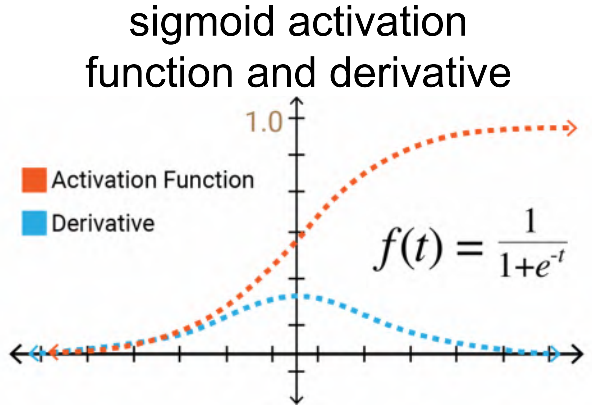
A feed forward artificial neural network (ANN) was trained in real-time to lean a model of the system that could be used to estimate structural responses at unmeasured locations:

- Trained on time-domain acceleration data.
- 1 hidden layer, 25 nodes, and a sigmoid activation function trained over 50 iterations.
- Computations were executed in double precision floating point.





A linear surrogate model is used for this work



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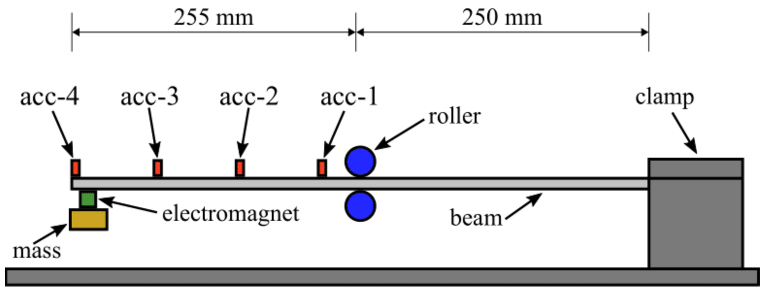
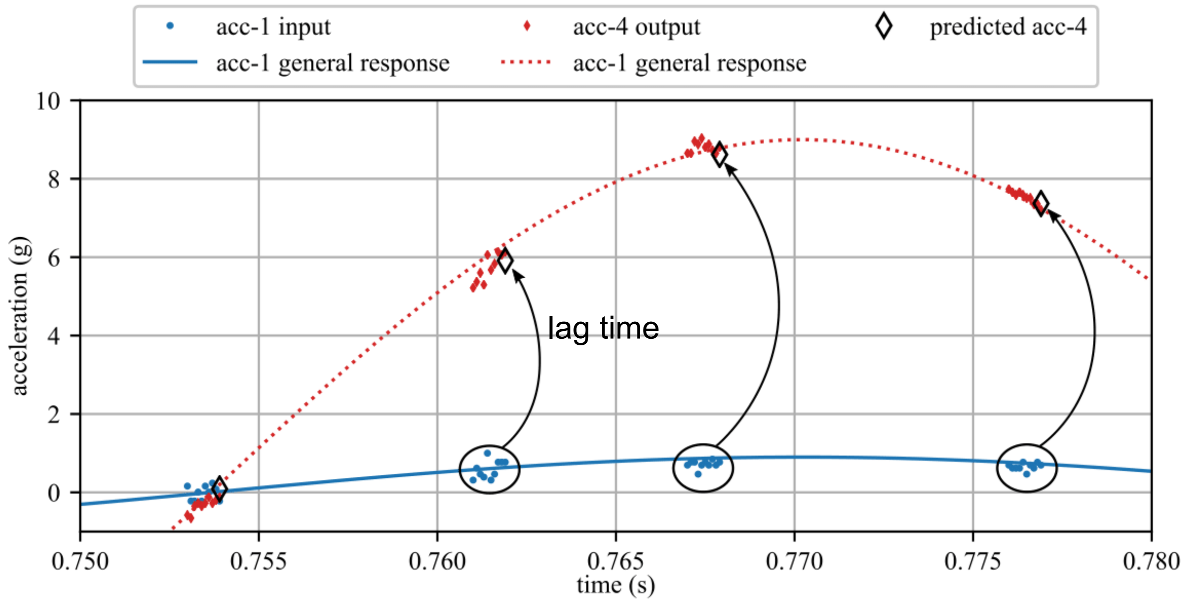
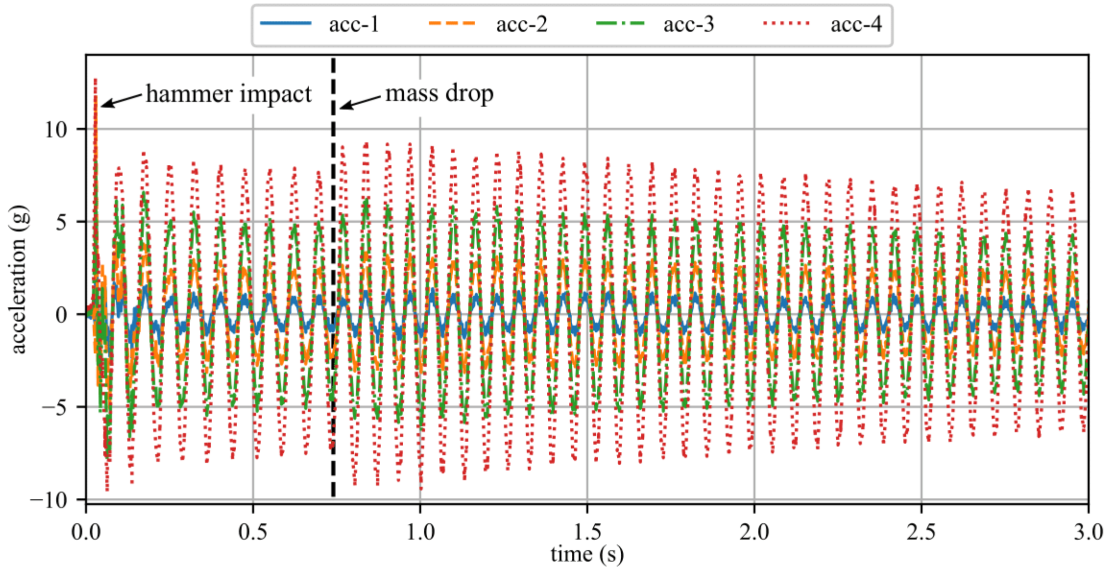
Experimental Validation

- An automated mass drop on the DROPBEAR was used to simulate a high-rate dynamic event:
- The network was trained using acc-1 as the input and acc-4 as the output.
- An average computation time of 8 ms is obtained







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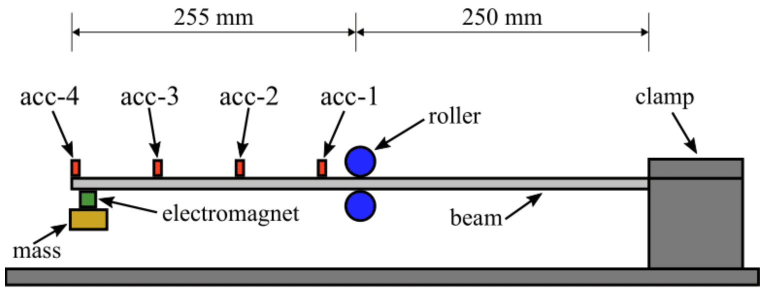
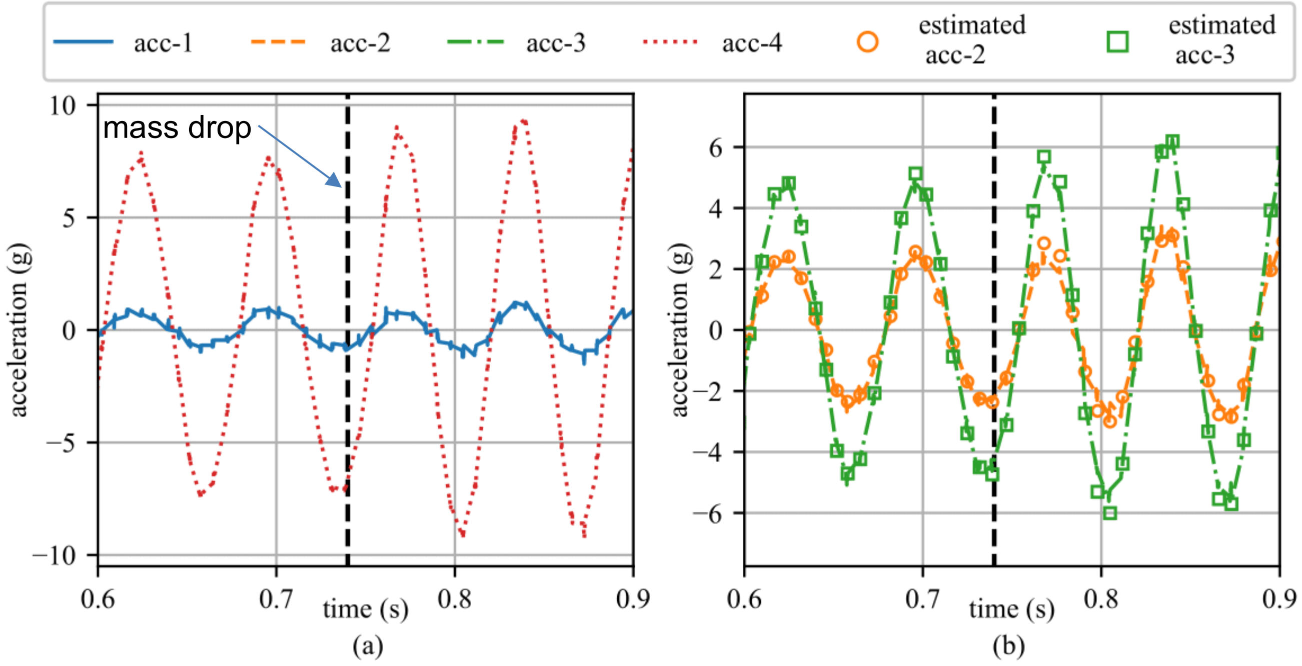
Experimental Validation

Benefits of the proposed method

- Relatively low level of latency (8 ms)
- Results demonstrate that an ANN of limited scale can be used as a data-based observer to track the system state though the mass drop.
- Successfully estimated the acceleration response at unobserved locations.





Challenges with the proposed method

- The need for labeled training data limits the applications of the proposed method.

There are challenges (large computational cost) with scaling the system as backproagation is O(n^5).

- The method does not generate a physical model of the system (useful for decision making).

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Research Endeavor 2: Real-Time Model Updating Through Error Minimization

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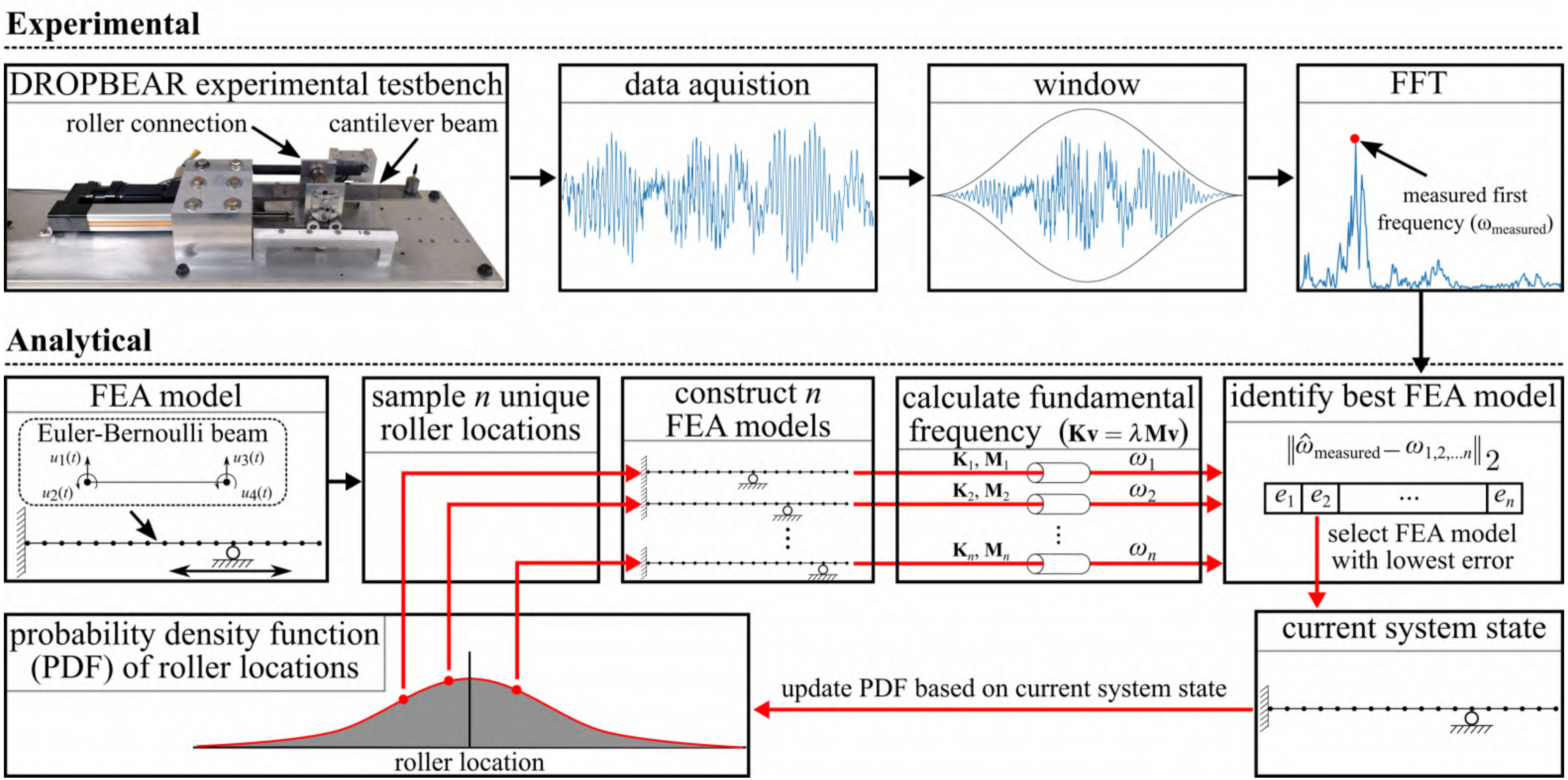
Real-Time Model Updating Through Error Minimization

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

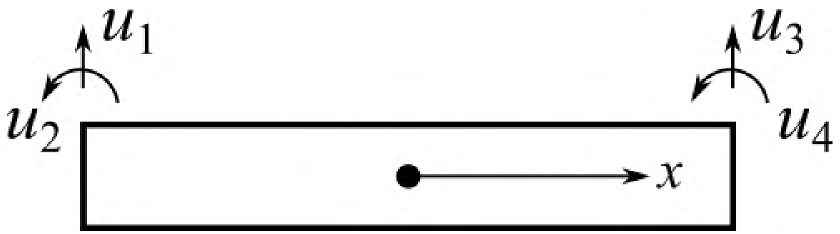


Background: Euler-Bernoulli Beam

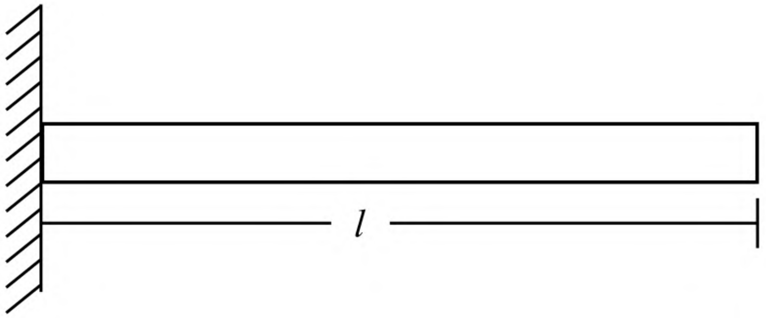
Euler–Bernoulli beam theory:

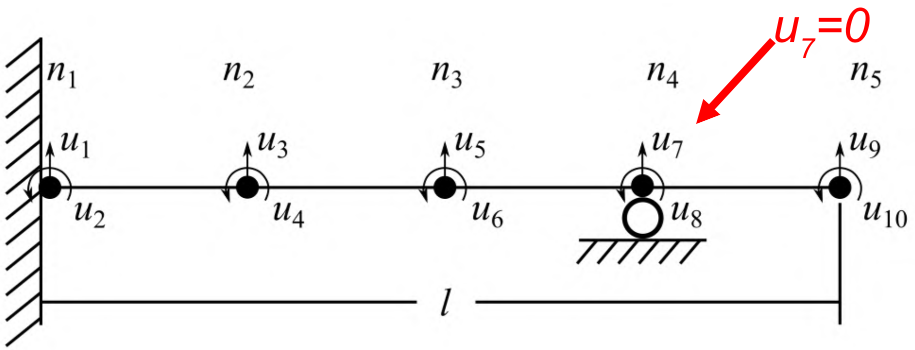
- Is a linear approximation of the response of a beam under load.
- Only applicable to small loads applied in the lateral direction.
- Plane sections remain plane and normal to the axis of the beam.
- Provides better predictions for thin beams than for thick beams (length-to-thickness < 20).

Euler–Bernoulli Beam Element



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





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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:

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

and:

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

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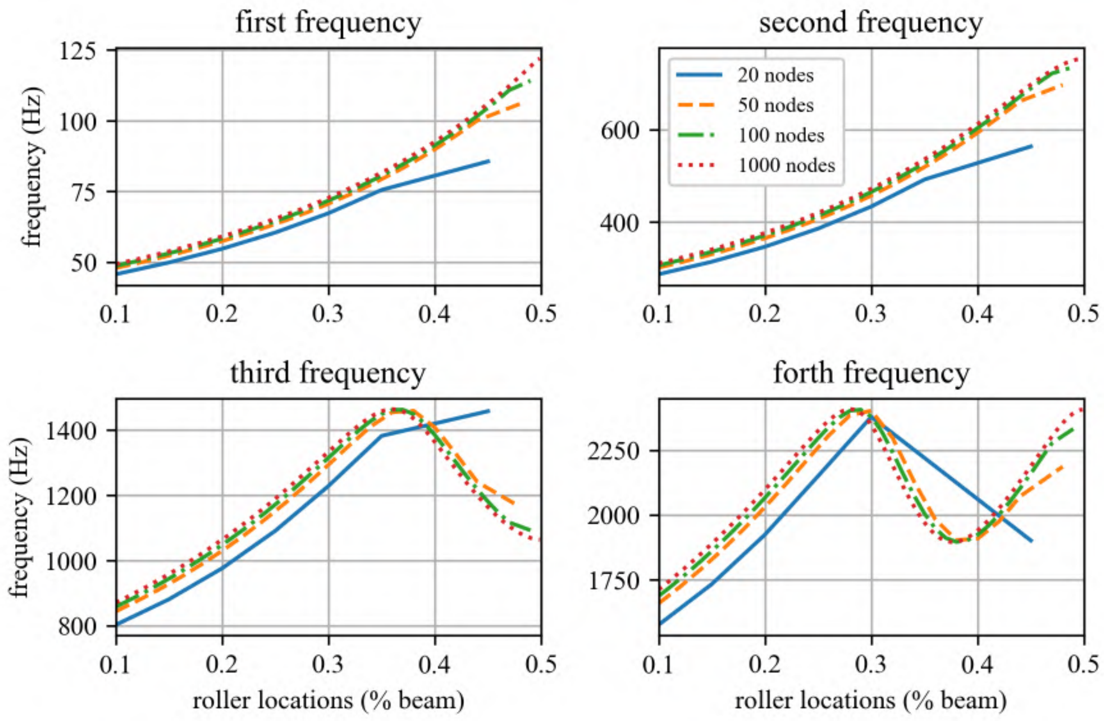
FEA Model Validation

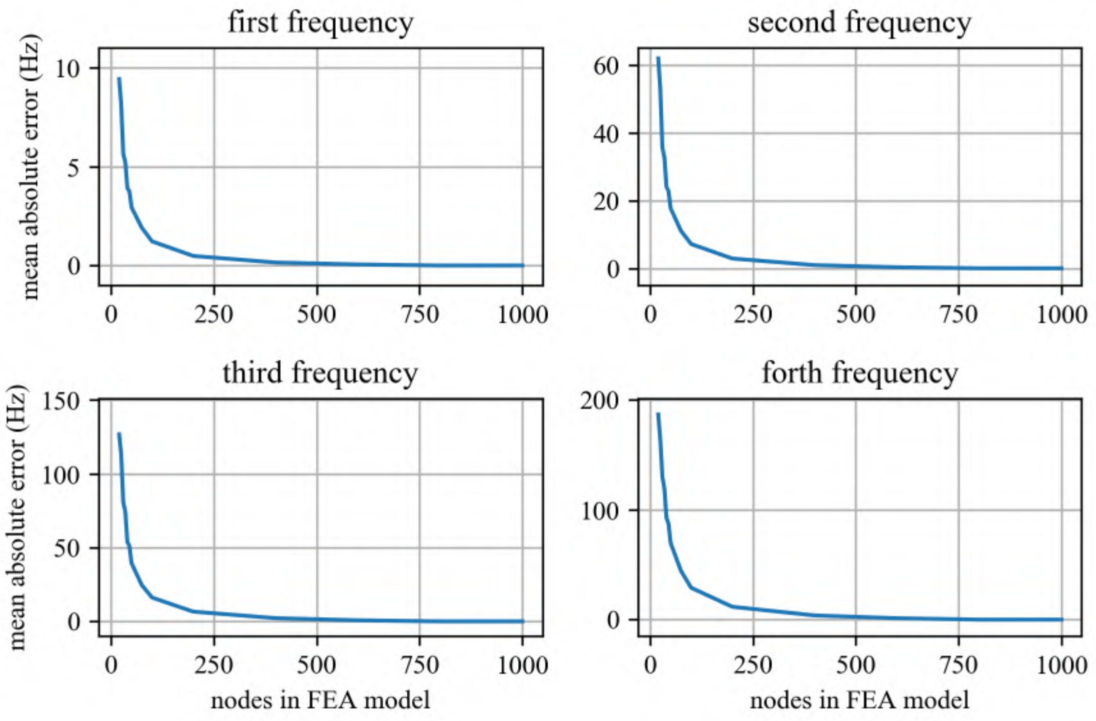
A 1-D FEA model of DROPBEAR was developed and validated:

- Interested in frequency response to a change in roller position
- After 100 nodes, the improvement in error is limited.

Frequency vs. Roller Location

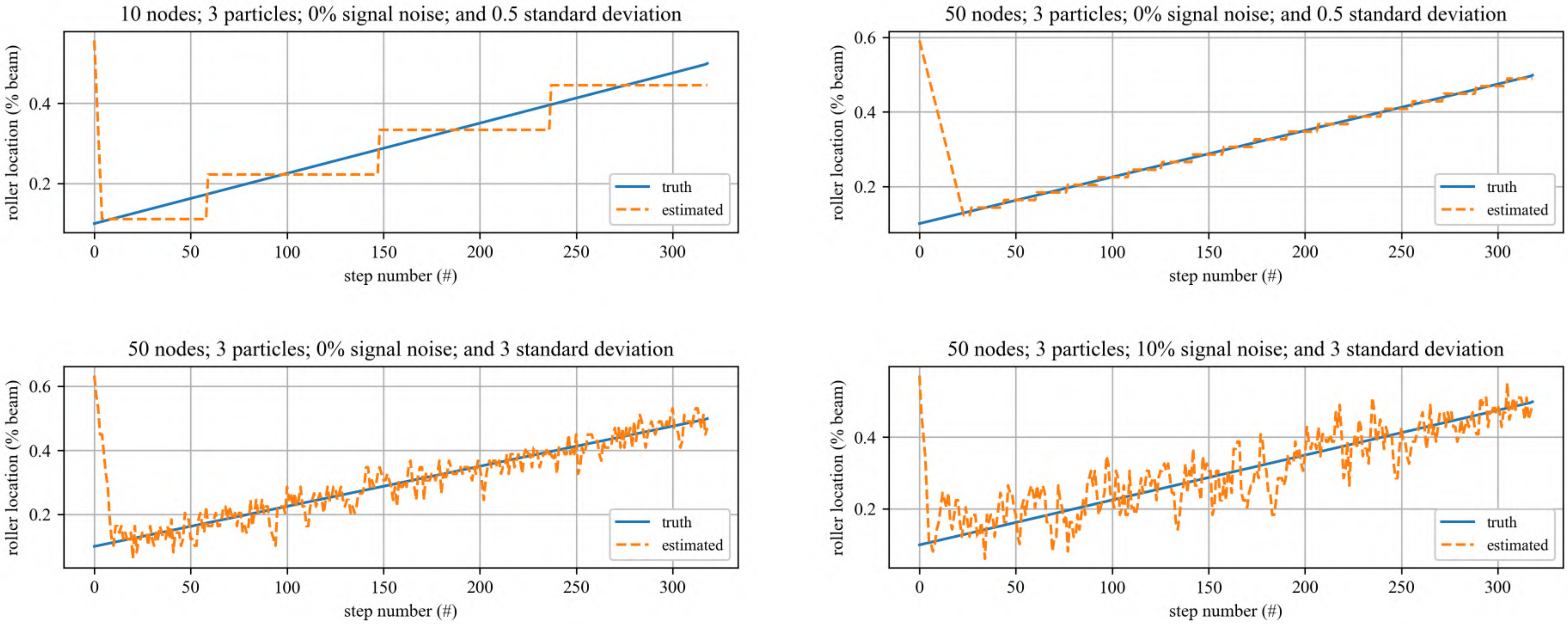


Error vs. number of Nodes in FEA Model



DROPBEAR Simulation Results

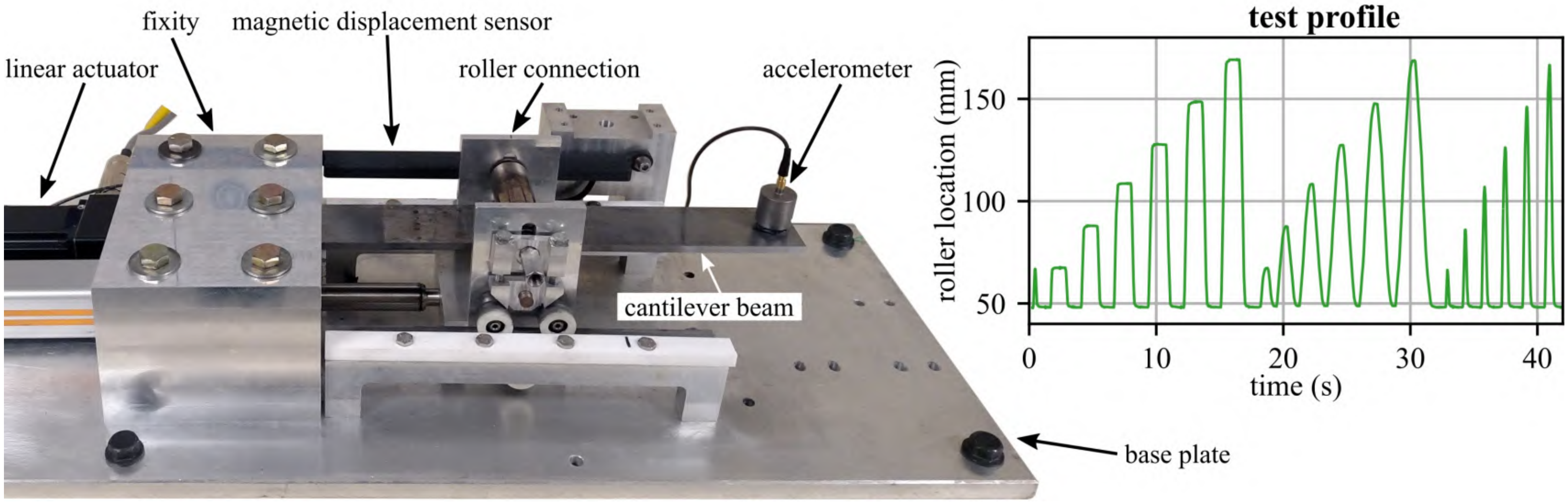
Used 1000 node FEA as ground truth in simulation.

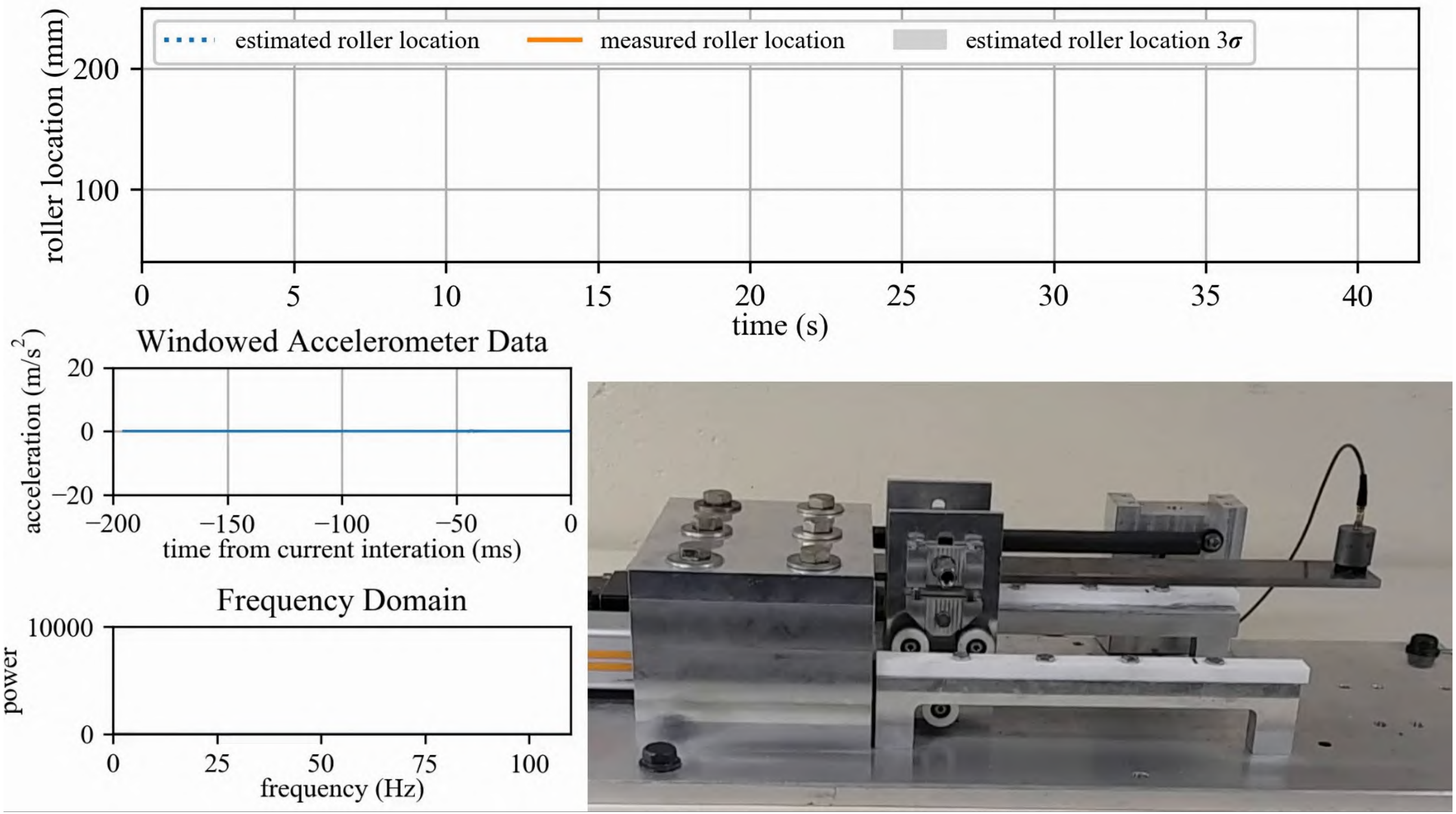


Experimental Validation

DROPBEAR was configured with a shorter beam (350mm) in order to generate higher frequencies:

- The cart provides the excitation to the beam and is fully automated.
- A sensitive accelerometer allows for testing with low levels of vibrations.





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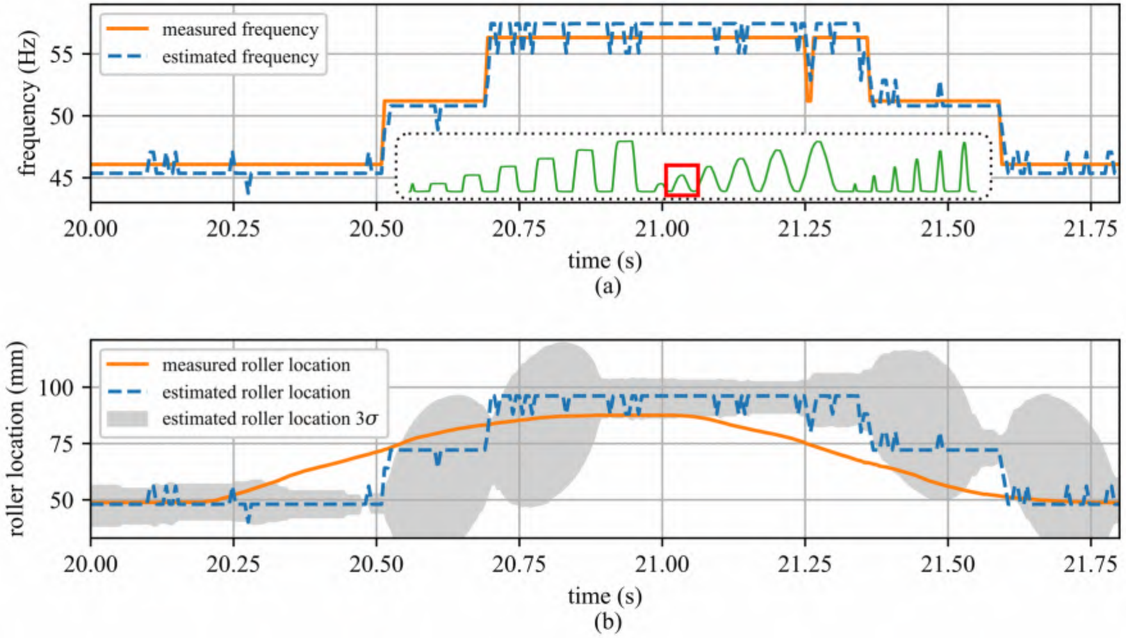
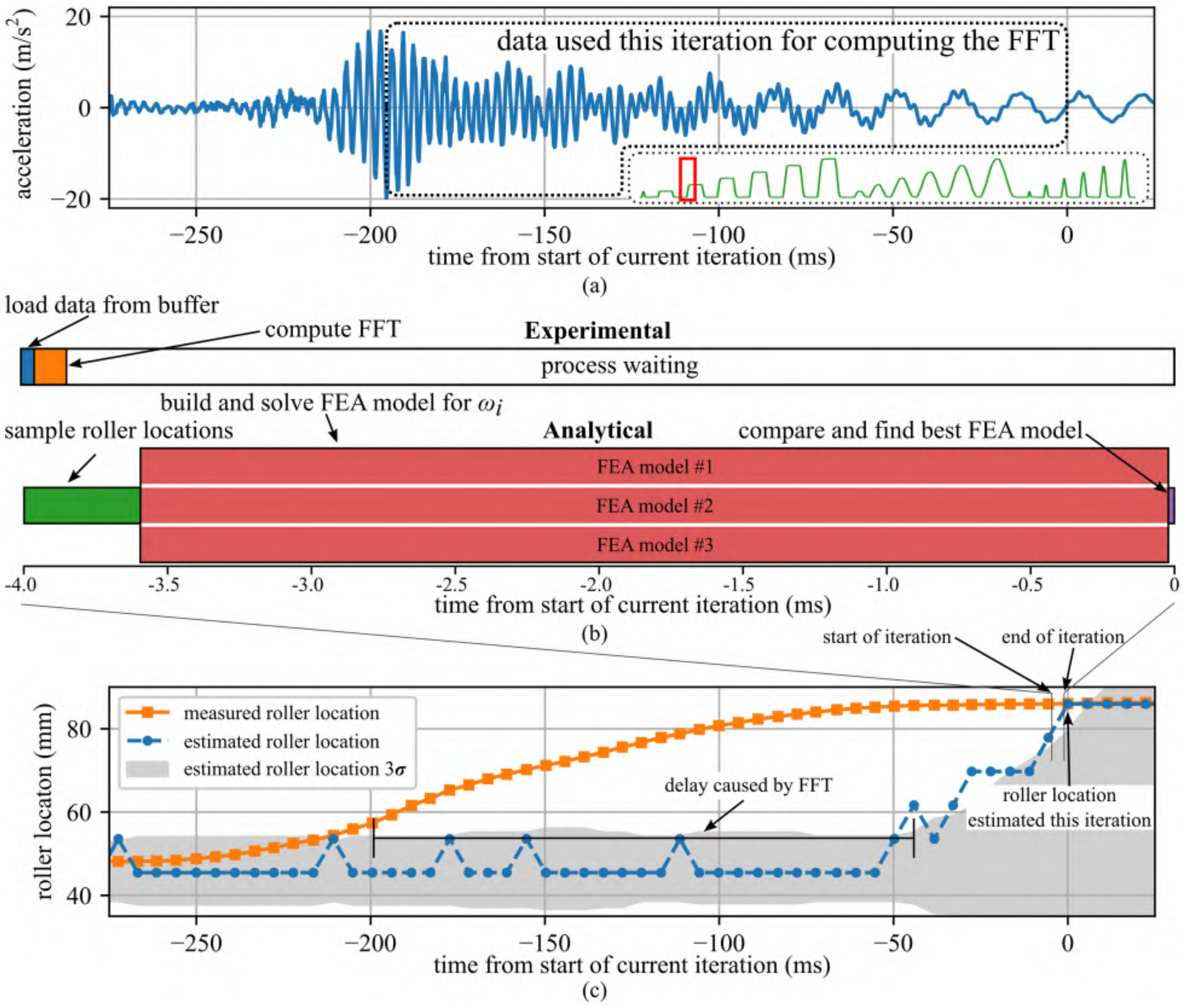
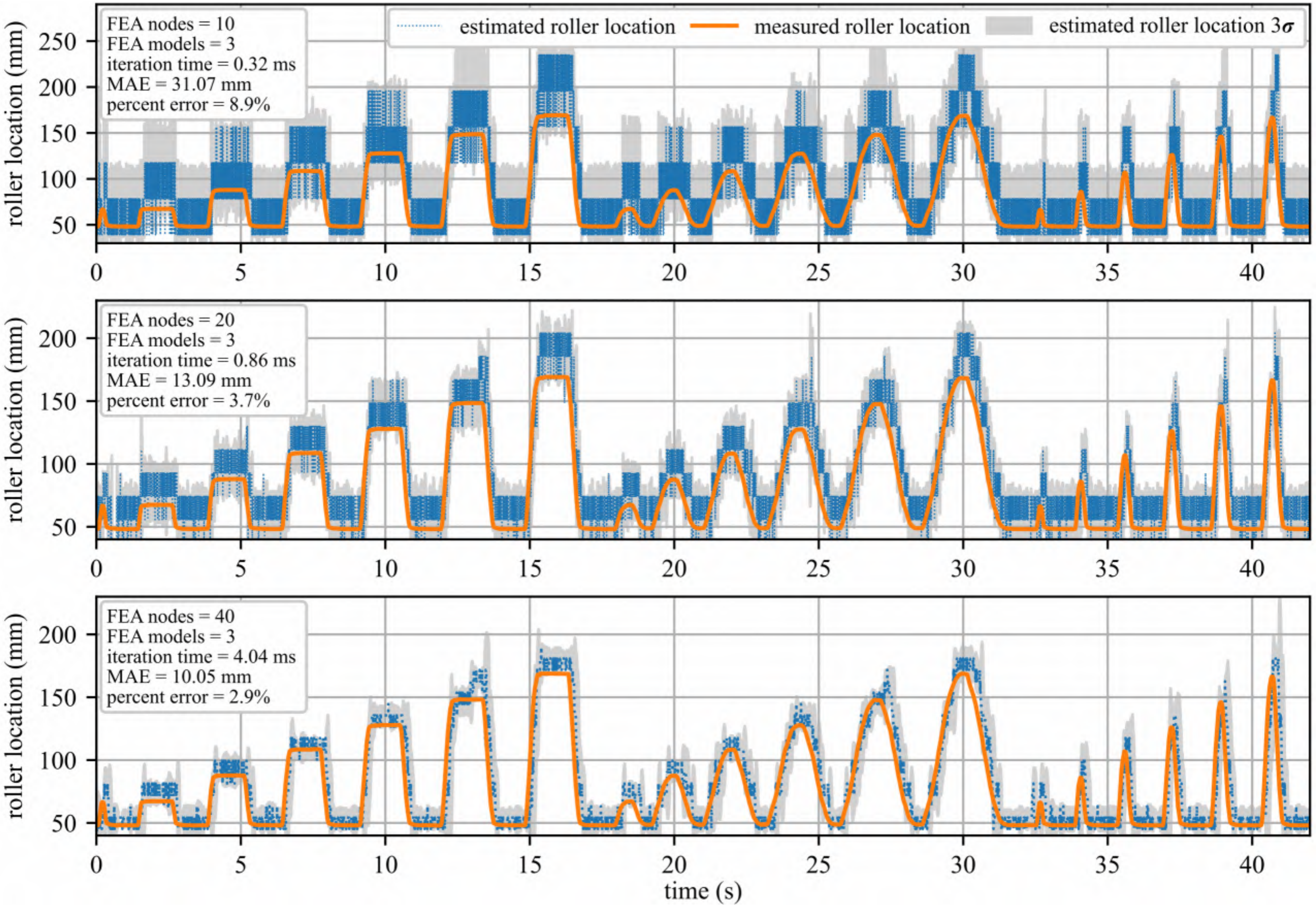
Experimental Results: Algorithm Timing

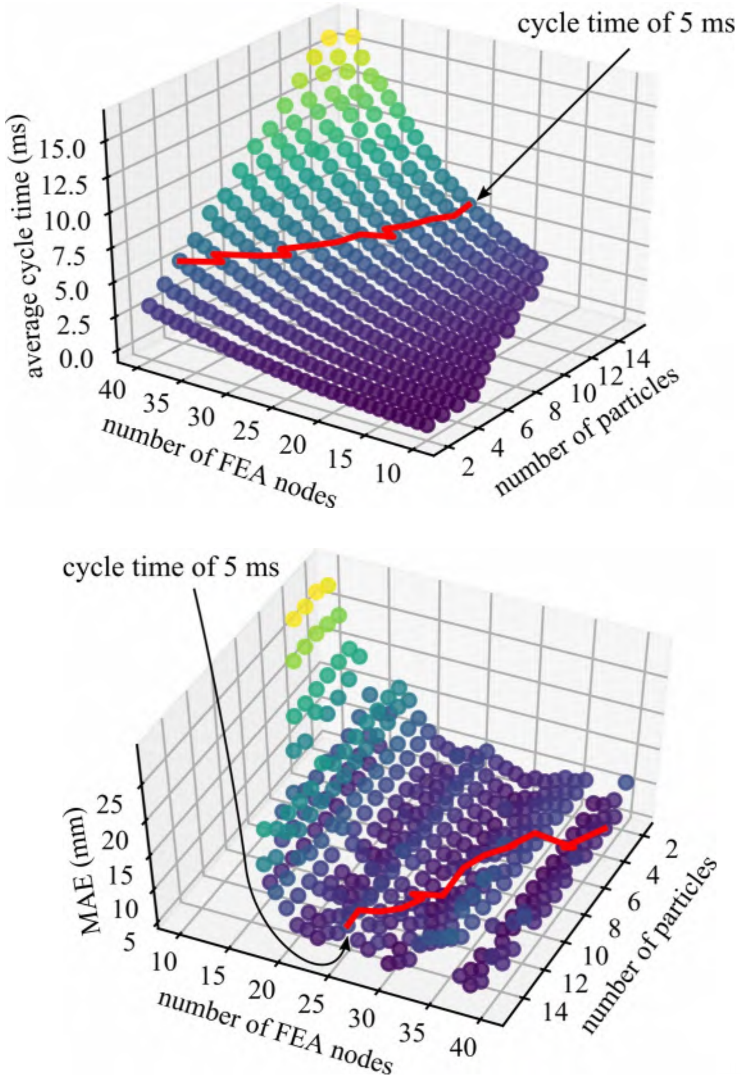
- Code run in parallel on multi-core processors using floating point precision variables.
- The FFT causes a delay in the estimation of the system.
- The length of the FFT is a function of the dynamics in the system.





Experimental Results: Model Updating

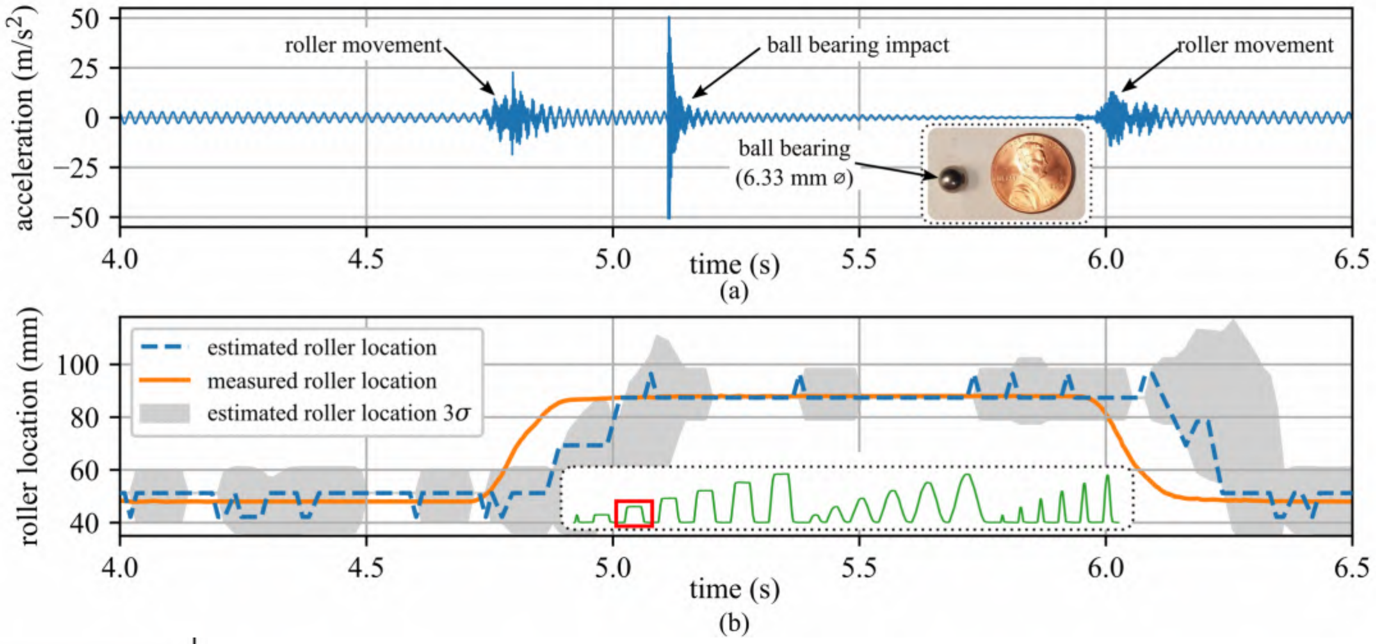


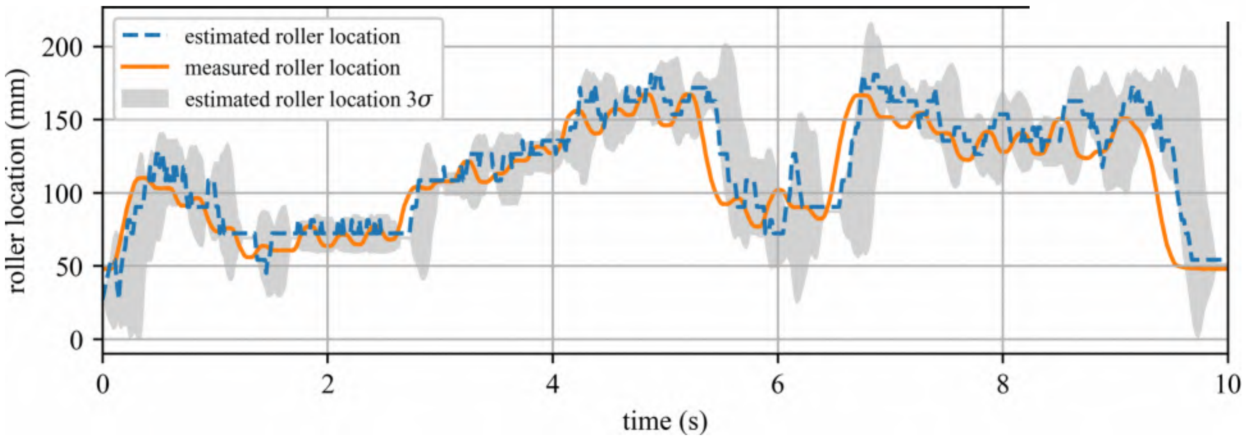


Experimental Results: Impact and Stochastic Testing

Impact Testing

- The frequency-based model updating algorithms can track the system state through an impact.
- This has benefits for system tracking of fuzzes in hard target penetrating systems.





Stochastic Testing

- A random data set was used to investigate the tracking capably of the proposed algorithm.
- Once the delay caused by the FFT is considered, the algorithm is show to accurately track the system state.

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Summary

Summary

High-Rate Dynamic Events

- Fuzes are a delicate payload that experience high-rate dynamic events.
- A real-time model updating technique could be used to increase the survivability of fuze components.

Research Endeavor 1: Real-Time Training of an Artificial Neural Network

- A neural network was trained in real-time to lean a model of the system that could be used to estimate structural responses at unmeasured locations.
- Experimental results demonstrated that a model of the system could be trained with a latency of 8 ms.
- The lack of a real physical model limits the applicability of the proposed algorithm.

Research Endeavor 2: Real-Time Model Updating Through Error Minimization

- A model updating technique based on error minimization was proposed and experimentally validated.
- Experimental results demonstrated low-latency model updating of the DROPBEAR.
- The proposed algorithms is capable of tracking the system through impact events.

THANKS!

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