EDGE-COMPUTING FOR STRUCTURAL HEALTH MONITORING ON RESOURCE CONSTRAINED DEVICES

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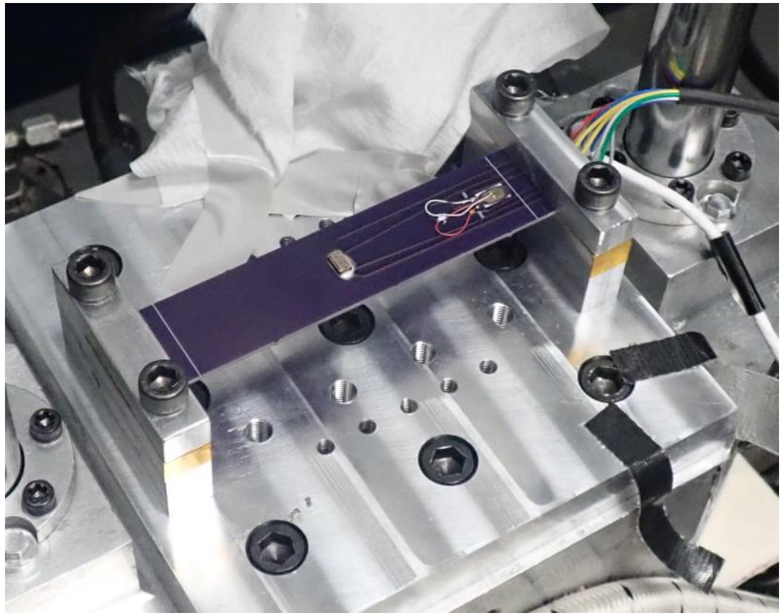
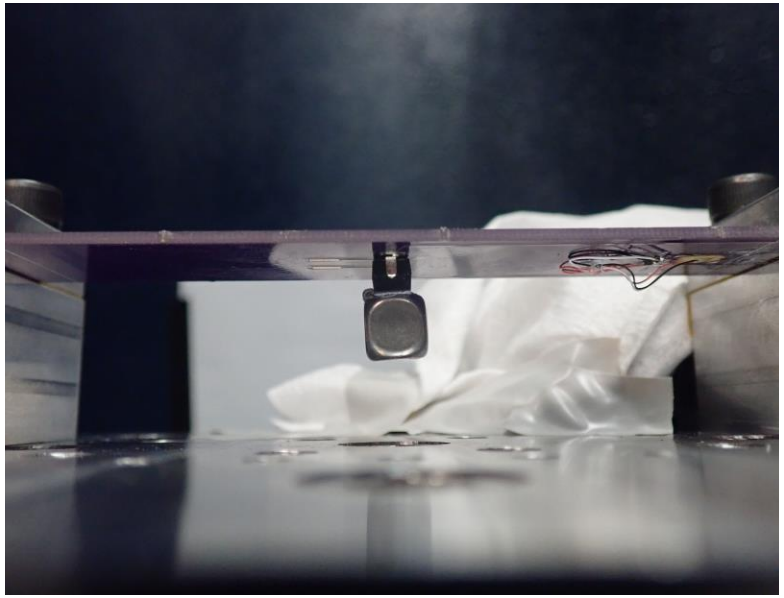
OUTLINE

- Introduction and contributions
- Drone-deployable sensor packages
- Embedded sensing in electronics for SHM
- Conclusions
- Future directions







INTRODUCTION

- Structural health monitoring
  - Assess condition of structures
  - Used in:
    - Buildings, bridges, aircraft, ships, electronics
  - Vibrations can reveal damage
    - Accelerometers, FFTs
  - Healthy structures are predictable
  - Damage alters frequencies
  - Traditional SHM relies on complex on-site tests and off-site data processing
  - Edge-computations can be made for preliminary examinations to increase safety and accelerate decision-making

https://dunganeng.com/about-dungan/our-company/

https://www.globalwaterforum.org/2022/11/10/mind-the-gap-between-perception-and-reality-of-bridge-collapses-over-water/

CONTRIBUTIONS

Main:

The development of scalable, frequency-based SHM frameworks that enable rapid damage detection using edge computing on resource-constrained devices.

Supporting:

1) The design and deployment of UAV-compatible, edge-computing sensor nodes.

2) An experimental validation of onboard frequency-based damage detection.

PUBLICATIONS

- Journal Papers:
  - [1] **Ryan Yount**, Joud N. Satme, and Austin R.J. Downey. Edge Computing on Sensor Packages for Vibration-Based Structural Health Monitoring. Manuscript in preparation, 2025. (in development)
- Peer-Reviewed Conference Proceedings:
  - [6] Qi M. Zheng, Joud N. Satme, Austin R.J. Downey, Korebami O. Adebajo, and **Ryan Yount**. Progress Towards Autonomous UAV Deployment of Sensor Package for Infrastructure Monitoring Using Deep Learning Control. ASME International Mechanical Engineering Congress and Exposition (IMECE), 2025. (in development)
  - [5] Joud N. Satme, **Ryan Yount**, Spencer Schwartz, Austin R.J. Downey, and Yue Ling. A Study on the Effects of the Ceiling Effect on a Propeller Thrust Force. ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC-CIE), 2025. (under review)
  - [4] Zhymir Thompson, **Ryan Yount**, Jacob Dodson, Adriane Moura, and Austin R.J. Downey. End-Of-Life Prediction For Solder Joints In Electronic Systems Experiencing Low-Cycle Fatigue Under Impact Loading. ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC-CIE), 2025. (under review)
  - [3] **Ryan Yount**, Kerry Sado, Austin R.J. Downey, Enrico Santi, Jamil Khan, Bin Zhang, and Kristen Booth. Multi-Domain Load Profiling of Electric Marine Vessels Under Simulated Sea States. IEEE Electric Ship Technologies Symposium (ESTS), 2025. (under review)
  - [2] Joud N. Satme, **Ryan Yount**, Nikita Goujevskii, Luke Jannazzo, and Austin R. J. Downey. Sensor package deployment and recovery cone with integrated video streaming for rapid structural health monitoring. In ASME 2024 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2024. American Society of Mechanical Engineers, September 2024. doi:10.1115/smasis2024-140435
  - [1] Puja Chowdhury, Joud N. Satme, **Ryan Yount**, Austin R. J. Downey, Sadik Khan, Jasim Imran, and Laura Micheli. Classifying soil saturation levels using a network of UAV-deployed smart penetrometers. *In ASME 2023 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2023*. American Society of Mechanical Engineers, September 2023. doi:10.1115/smasis2023-111009

PUBLICATIONS

- Conference Proceedings:
  - [6] **Ryan Yount**, Trotter Roberts, Jacob Dodson, Adriane Moura, and Austin R.J. Downey. Experimental Analysis to Enable Low-Latency Structural Health Monitoring for Electronics in High-Rate Dynamic Environments. *Springer Nature Switzerland*, 2025
  - [5] Trotter Roberts, **Ryan Yount**, Jacob Dodson, Adriane Moura, and Austin R.J. Downey. Towards active structural control strategies for electronic assemblies in high-rate dynamic environments. *94th Shock and Vibration Symposium*, November 2024.
  - [4] **Ryan Yount**, Joud N. Satme, David Wamai, and Austin R. J. Downey. Edge processing for frequency identification on drone-deployed structural health monitoring sensor nodes. In Paul L. Muench, Hoa G. Nguyen, and Robert Diltz, editors, *Unmanned Systems Technology XXVI*. SPIE, June 2024. doi:10.1117/12.3013712
  - [3] **Ryan Yount**, Joud N. Satme, and Austin R.J. Downey. Frequency-based damage detection using drone-deployable sensor package with edge computing. In *Conference Proceedings of the Society for Experimental Mechanics Series*. Springer Nature Switzerland, August 2024. doi:10.1007/978-3-031-68142-4_9
  - [2] Joud N. Satme, **Ryan Yount**, Jason Smith, and Austin R.J. Downey. Case study for using open-source UAV-deployable wireless sensor nodes for modal-based monitoring of civil infrastructure. In *Proceedings of the 14th International Workshop on Structural Health Monitoring*, shm2023. Destech Publications, Inc., September 2023. doi:10.12783/shm2023/36832
  - [1] Joud N. Satme, **Ryan Yount**, Jacob Vaught, Jason Smith, and Austin R. J. Downey. Modal Analysis Using a UAV-Deployable Wireless Sensor Network, pages 75-81. Springer Nature Switzerland, August 2023. doi:10.1007/978-3-031-34942-3_8
- Conference Abstracts:
  - [1] Puja Chowdhury, Joud Satme, **Ryan Yount**, Austin R.J. Downey, Mohammad Sadik Khan, and Jasim Imran. Spatial mapping of soil saturation levels using UAV deployable smart penetrometers. *ASCE Geo-Institute 7th Annual Live Streaming Web Conference*, 2022
- Posters:
  - [2] *Ethan Ibarra, Austin Downey, Joud Satme, and* ***Ryan Yount****. Finite element analysis of an unmanned aerial vehicle deployment system. USC Summer Research Symposium, July 2024*
  - [1] ***Ryan Yount****, Joud Satme, Austin R.J. Downey, and Jasim Imran. Drone deliverable vibration sensor. UofSC Summer Research Symposium, July 2022*

PRESENTATIONS

- IMAC 2023
  - [1] Joud N. Satme, Ryan Yount, Jacob Vaught, Jason Smith, and Austin R. J. Downey. Modal Analysis Using a UAV-Deployable Wireless Sensor Network, pages 75-81. Springer Nature Switzerland, August 2023. doi:10.1007/978-3-031-34942-3_8
- IMAC 2024
  - [1] Ryan Yount, Joud N. Satme, and Austin R.J. Downey. Frequency-based damage detection using drone-deployable sensor package with edge computing. In *Conference Proceedings of the Society for Experimental Mechanics Series*. Springer Nature Switzerland, August 2024. doi:10.1007/978-3-031-68142-4_9
- SPIE Defense + Commercial Sensing 2024
  - [1] Ryan Yount, Joud N. Satme, David Wamai, and Austin R. J. Downey. Edge processing for frequency identification on drone-deployed structural health monitoring sensor nodes. In Paul L. Muench, Hoa G. Nguyen, and Robert Diltz, editors, *Unmanned Systems Technology XXVI*. SPIE, June 2024. doi:10.1117/12.3013712
- AFRL Scholars Showcase
  - [1] Ryan Yount, Trotter Roberts, Jacob Dodson, Adriane Moura, and Austin R.J. Downey. Experimental Analysis to Enable Low-Latency Structural Health Monitoring for Electronics in High-Rate Dynamic Environments. *Springer Nature Switzerland*, 2025
- IMAC 2025
  - [1] Ryan Yount, Trotter Roberts, Jacob Dodson, Adriane Moura, and Austin R.J. Downey. Experimental Analysis to Enable Low-Latency Structural Health Monitoring for Electronics in High-Rate Dynamic Environments. *Springer Nature Switzerland*, 2025

DRONE-DEPLOYABLE SENSOR PACKAGE

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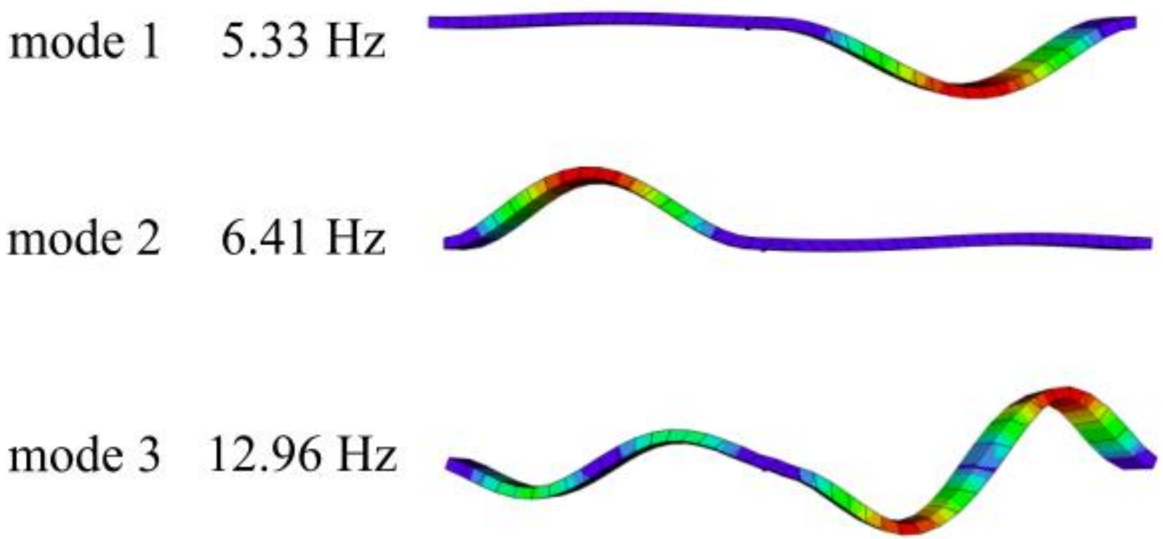
- Deployment and retrieval system
- Sensor hardware
- Edge computing algorithm
- Can be used after natural disasters to assess the safety of infrastructure

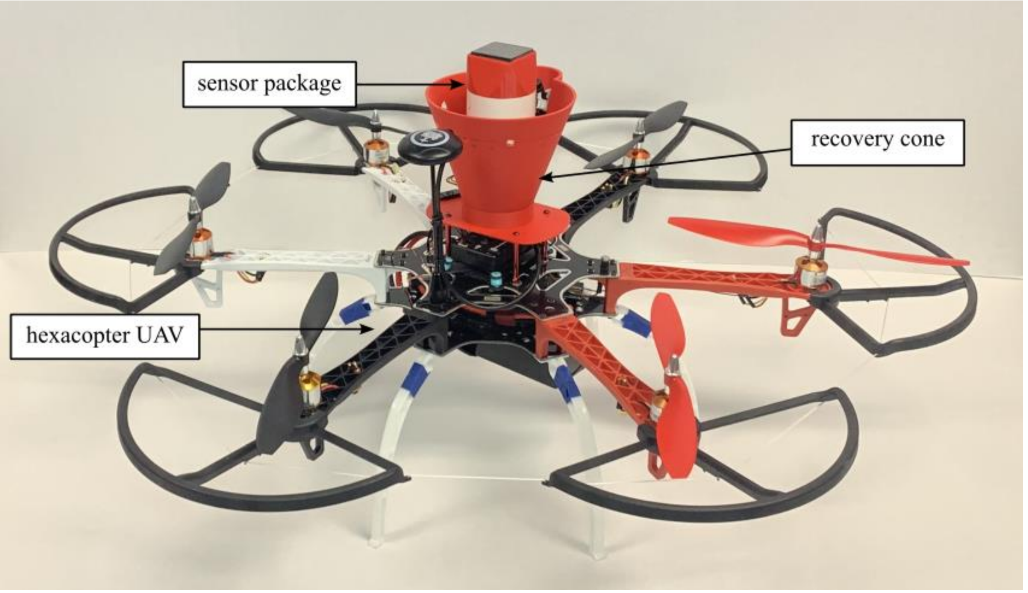
DRONE-DEPLOYABLE SENSOR PACKAGE

- Can be deployed following natural disasters
  - To assess safety before manned operations
- Intended for use with bridges



DEPLOYMENT AND RETRIEVAL SYSTEM

- Electropermanent magnet
  - Brief 5 V pulse is applied that changes polarity
- Low power usage
- 3D printed retrieval cone
  - Guides sensor package



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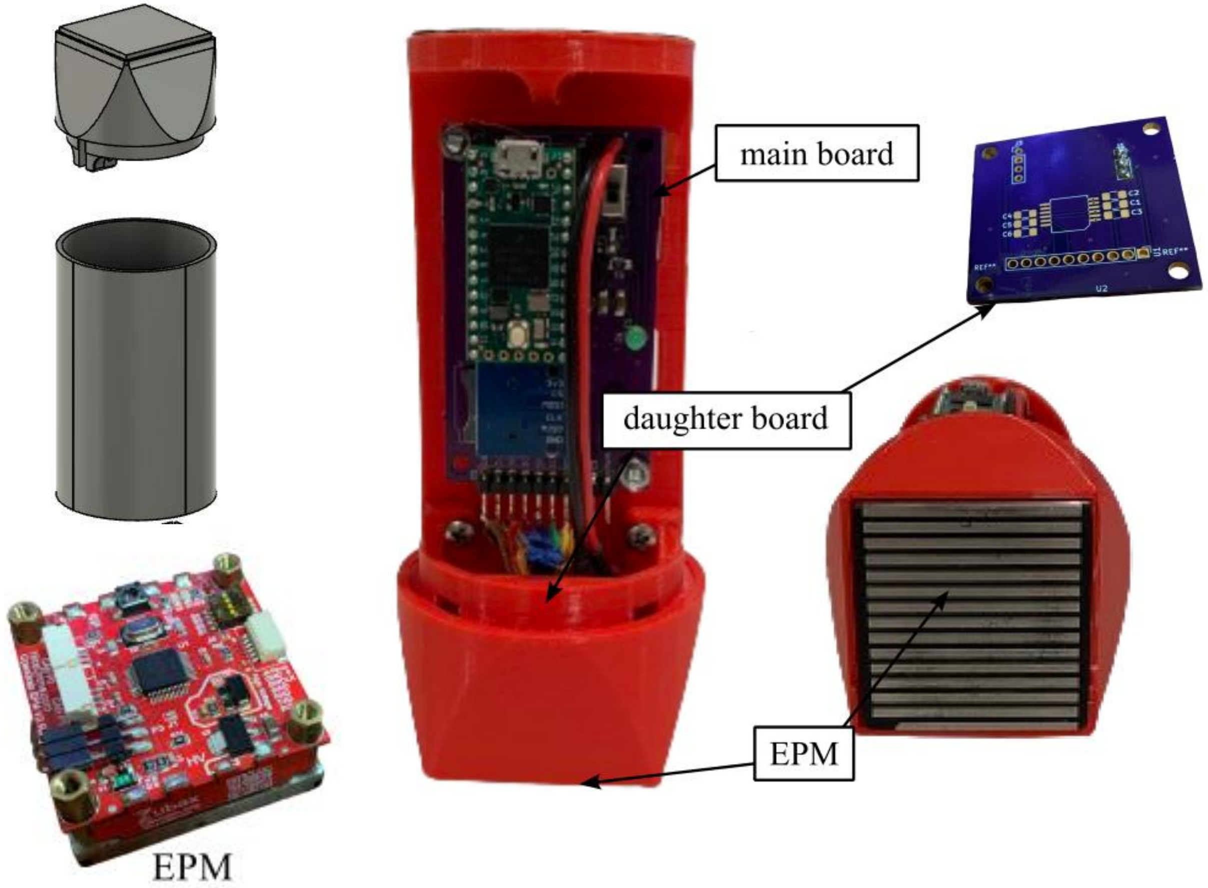
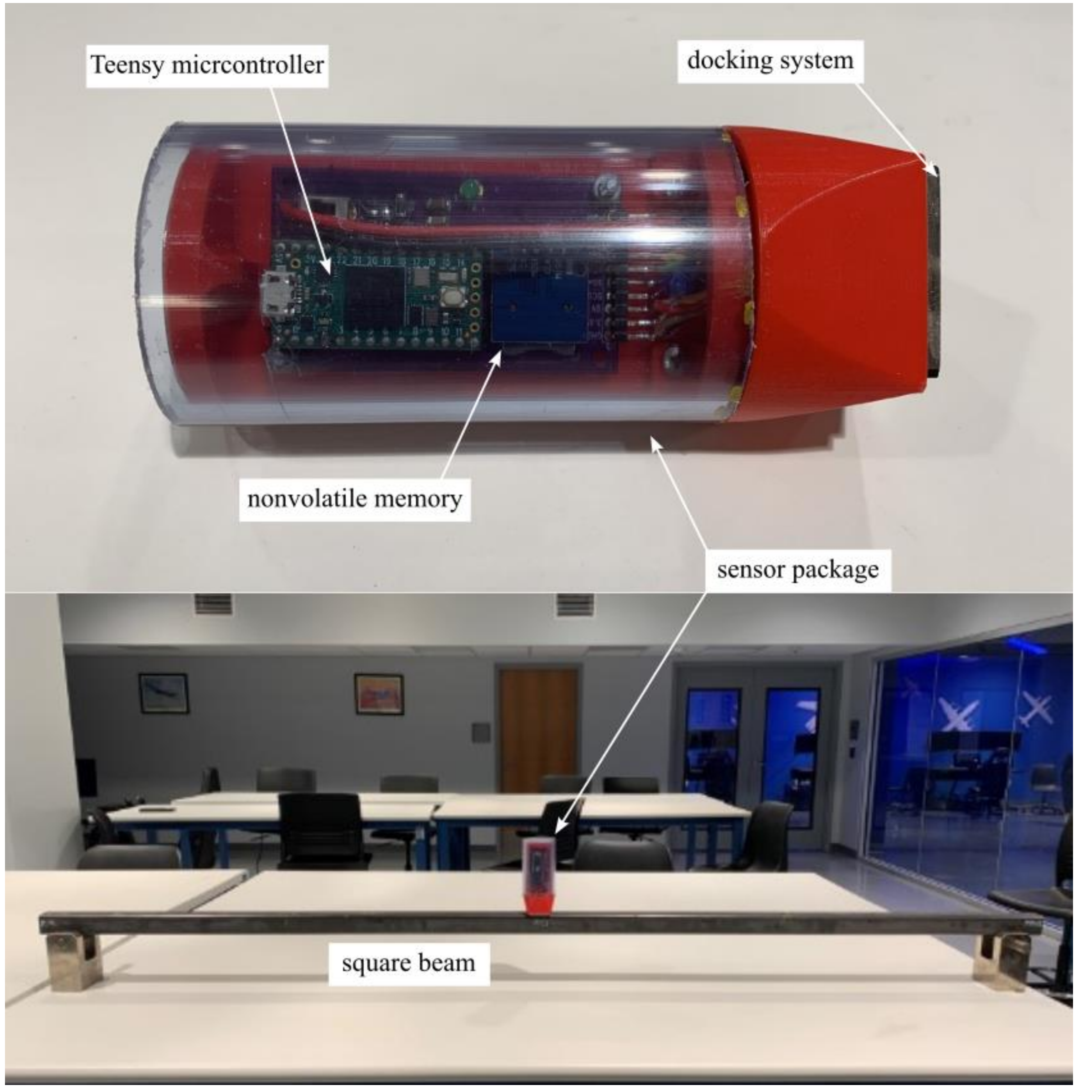
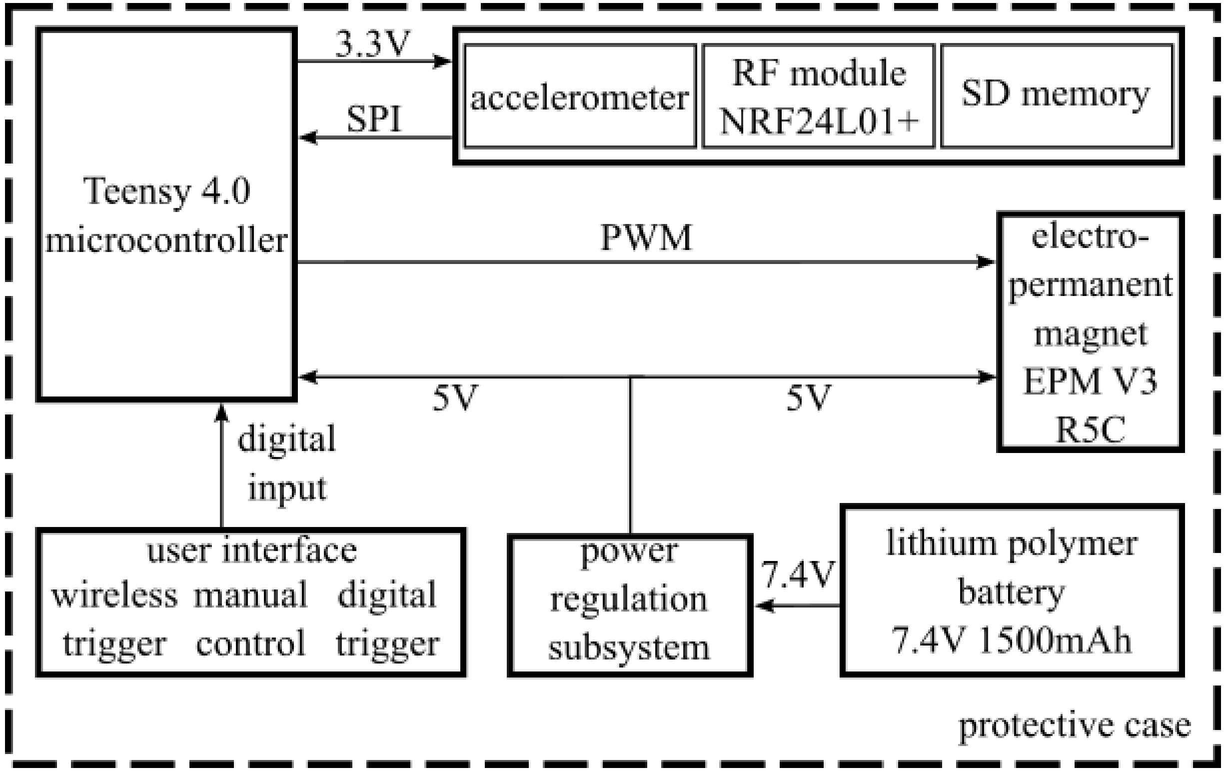
SENSOR HARDWARE





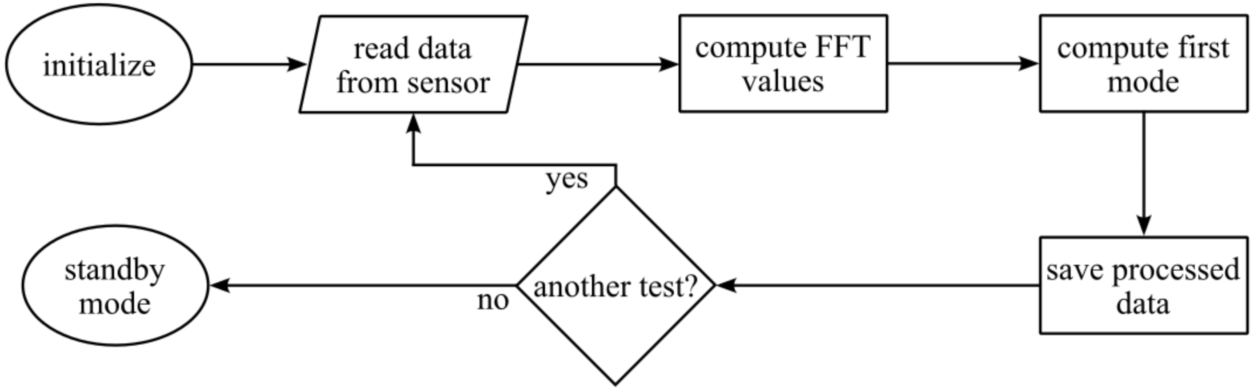
SENSOR HARDWARE

- Hardware
  - Processor
  - Accelerometer
  - Electropermanent magnet
  - Battery
  - Transceiver
  - Real-Time Clock



SENSOR ALGORITHM

- Edge-computation for rapid data-acquisition
- 16,384 max samples (currently)
- 1600 samples/s
- Data stored in nonvolatile memory to clear up dynamic memory for later processes
- Post-data collection, Cooley-Tukey FFT is computed
  - Divided into even and odd indexed points with separate FFTs, which later become combined



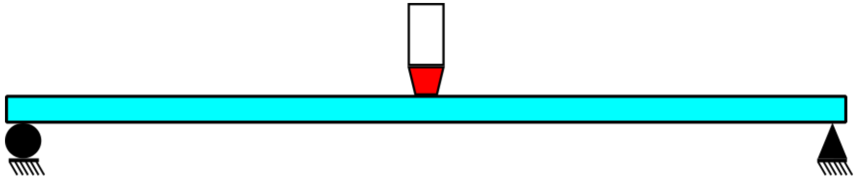
COMPUTATIONAL EFFICIENCY

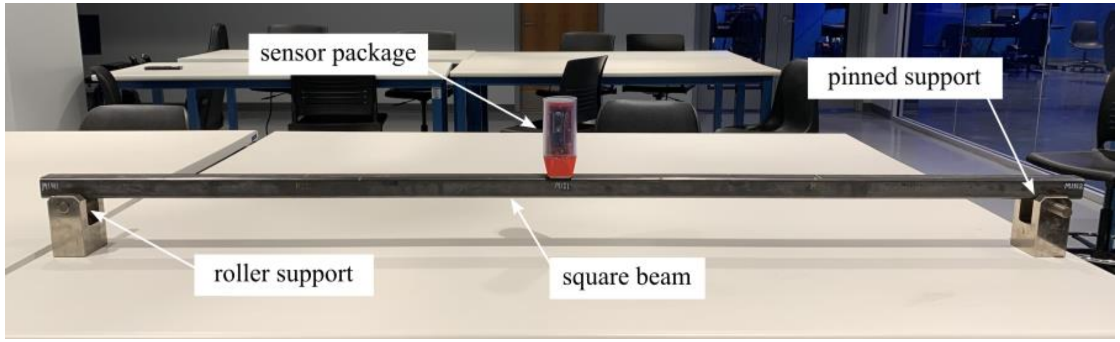
- Teensy 4.0 has ample memory for complex computations
- The Arduino toolchain is used for stable, continuous operation
- Hardware performance is profiled using GNU gprof
  - Insights into execution times
- Data collection is the most time-consuming because it is at a set time
- The timing analysis was focused on crucial functions of the algorithm’s performance
- 30 benchtop profiling runs were executed with consistent results

process	time (s)	cumulative time (s)	percent of total time (%)
data collection	10.24	10.24	51.07
read sensor	4.43	14.67	22.07
SD card read	0.05	19.54	0.27
SD card write	0.01	19.88	0.07
FFT computation	0.01	19.90	0.07
numeric conversions	0.00	20.01	0.01

STRUCTURE TESTING

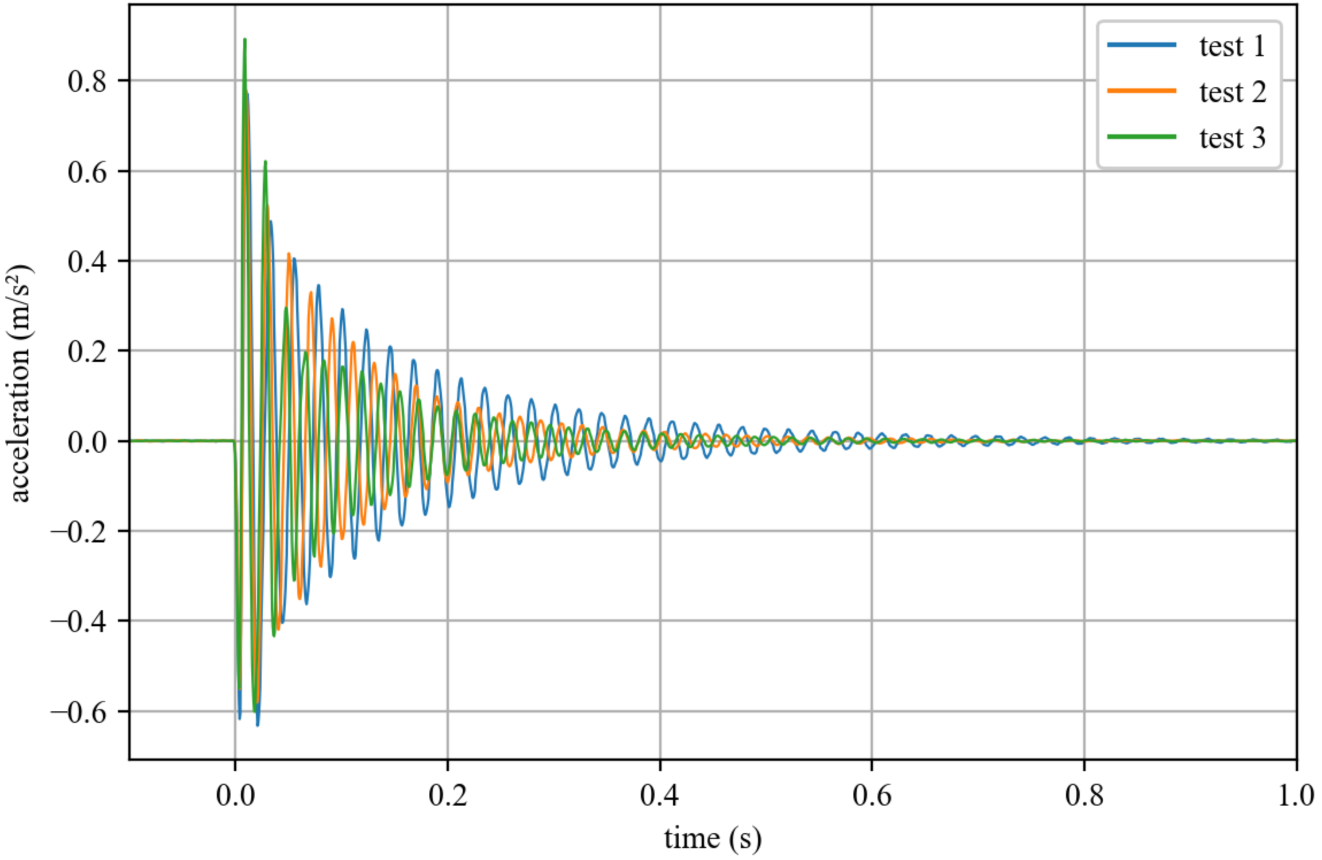
- Investigated vibrational behavior of a square stock beam with pinned and roller supports
- The primary goal was to assess the sensor's ability to measure across varying structural conditions
- A single sensor package was positioned in the center of the beam
- A series of three tests were performed, each intended to simulate a different structural state
  - Initially, both supports start evenly spaced from the center of the beam
  - After the first test, the left roller support was moved closer to the center incrementally





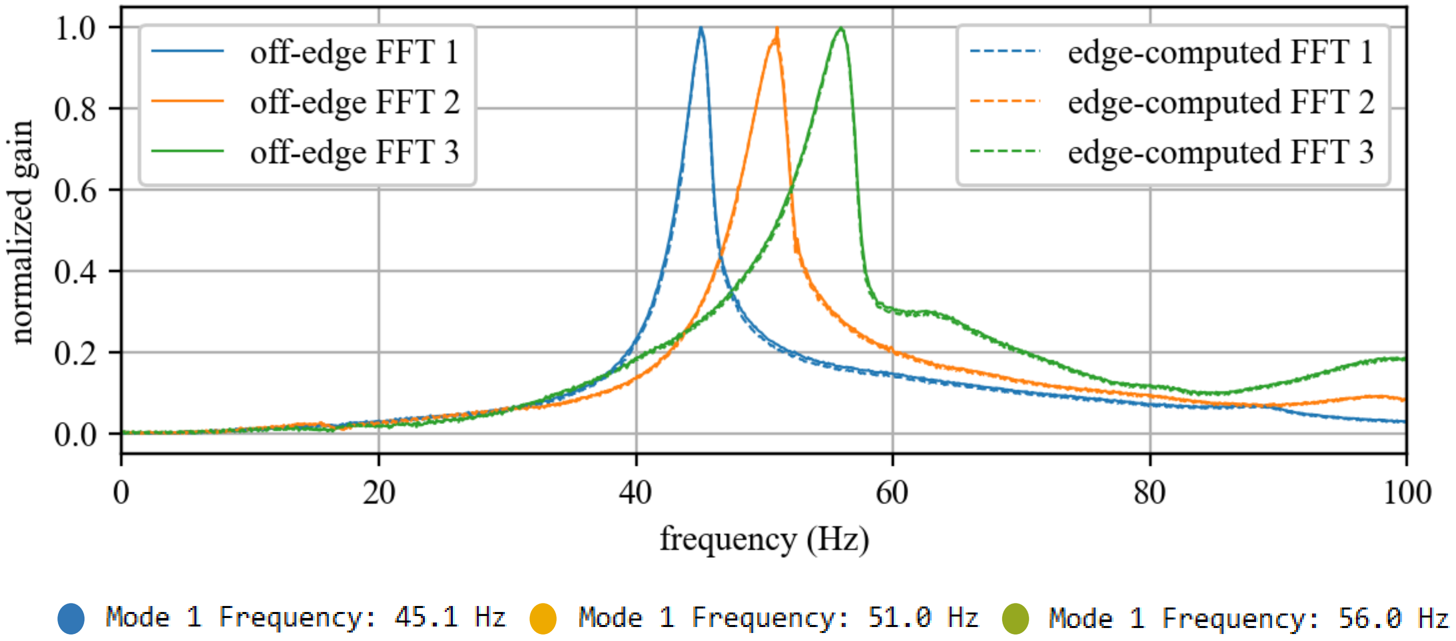
STRUCTURE TESTING

- A modal impact tool was used to create an impulse response in the beam
- During each test, the sensor package continuously recorded vibration data from the beam
- Each subsequent test shows a faster damping rate than the test before it
  - Showcases the sensor's ability to read different structural states
- The collected data was then subjected to FFT analysis
- The primary focus was to identify the first modal frequency of the system



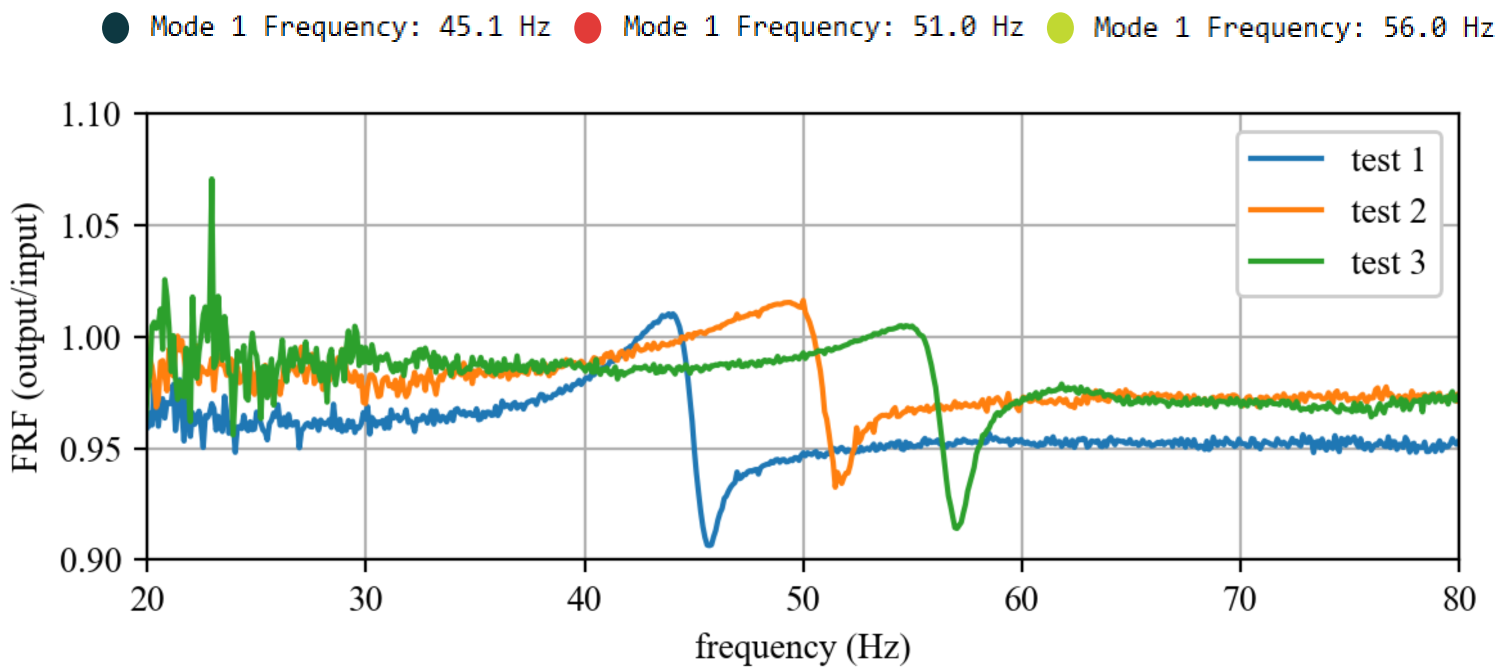
EXPERIMENTAL OUTCOMES

- Successful on-the-edge calculations
- Off-site NumPy algorithm used to use as a reference of FFT accuracy
  - RMSE: 0.0032, 0.0028, 0.0031
- Successful changes in natural frequency



EXPERIMENTAL OUTCOMES

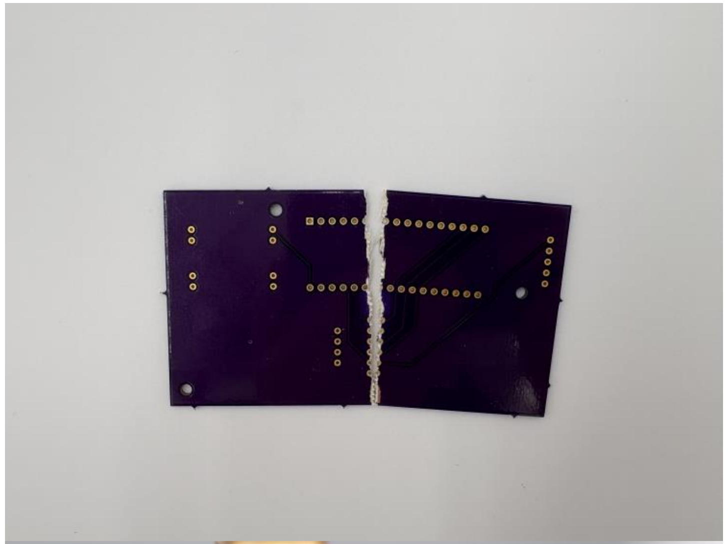
- Frequency response calculated to verify correlation between the two algorithms
- Flat at 1 would indicate the sensor FFT is as precise as the offsite program
- Largest difference around the modes is 0.094

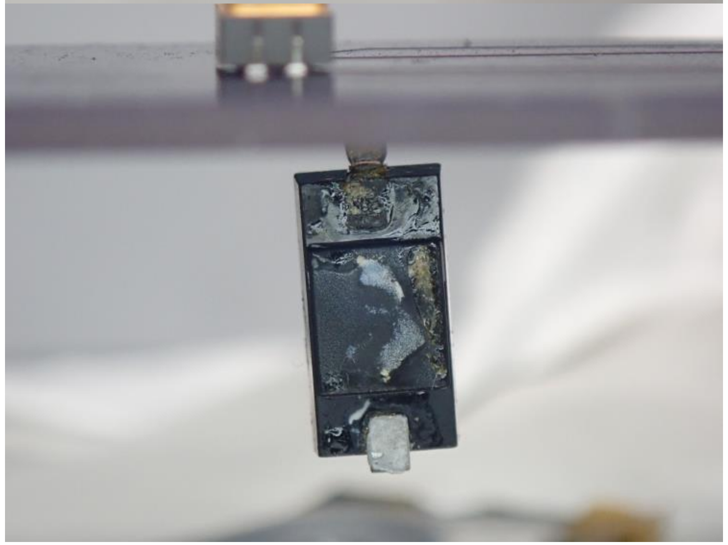


EMBEDDED SENSING IN ELECTRONICS

EMBEDDED SENSING IN ELECTRONICS

- Importance: Electronics in high-rate dynamic environments
- Problem: high-rate impacts can damage electronics, causing them to not function properly
- Proposal: Use embedded sensors and later combine them with an edge processor to detect damage
- Objective: Implement a frequency-based damage detection system in electronic assemblies





HIGH-RATE MECHANICAL SHOCK

- Mechanical Shock
  - Sudden change in force, position, velocity, or acceleration
  - Induces transient states in the system
  - Can excite system frequencies
  - Can lead to unpredictable responses within the structural integrity of components

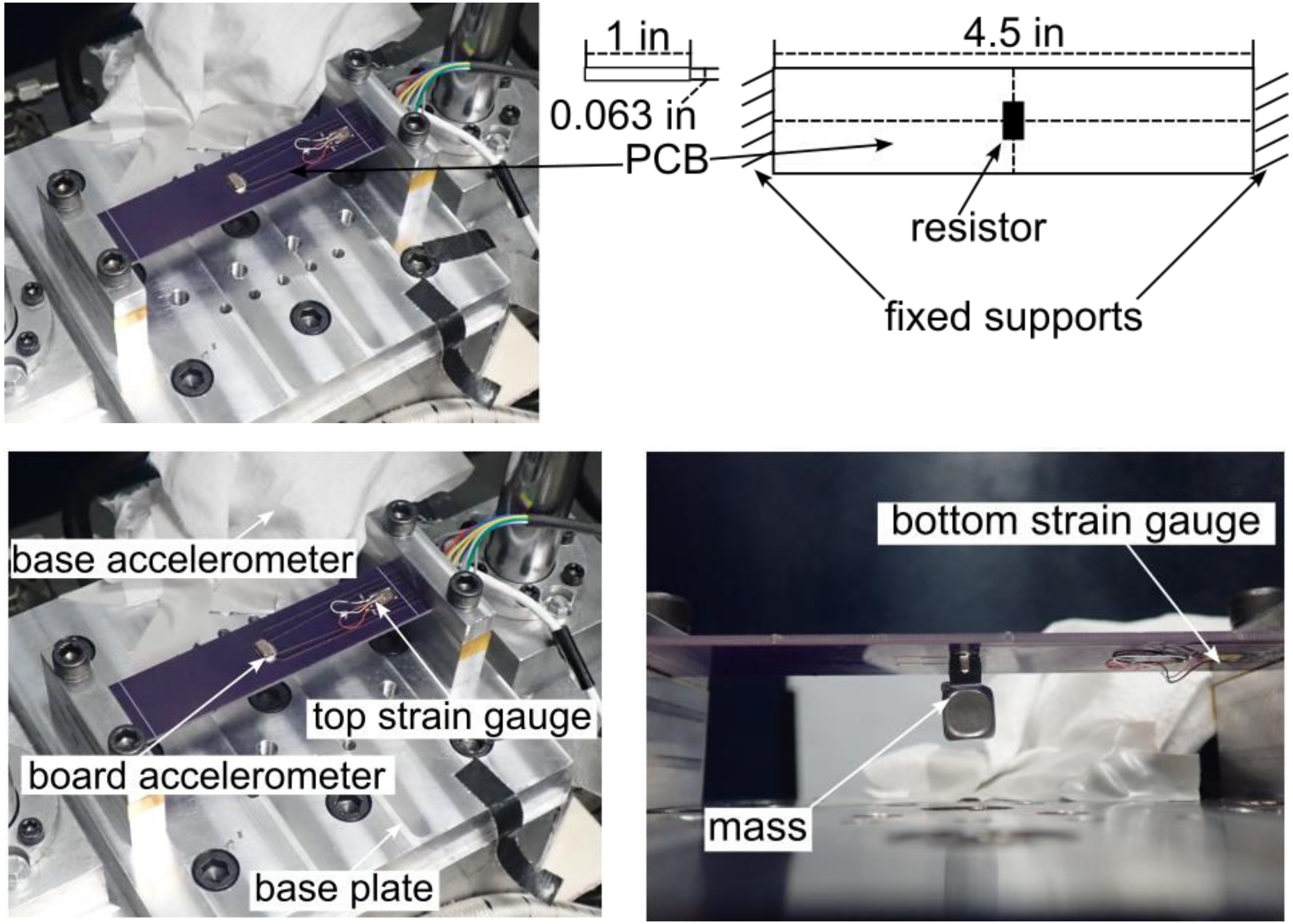
Blast against civil structures

Automotive impact and crashes

High Speed aircraft and airframes

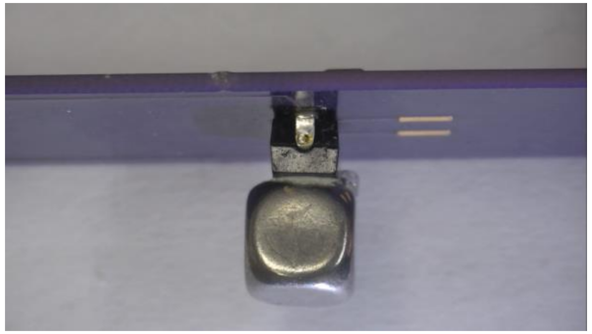
EMBEDDED SENSORS

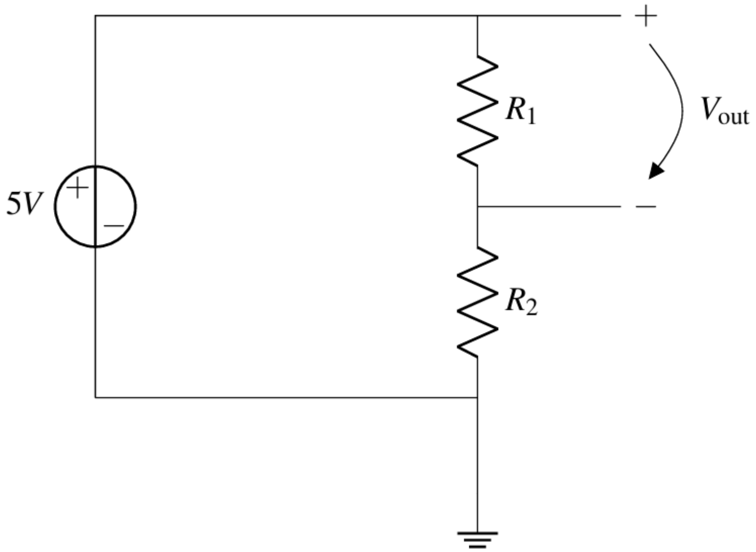
- Sensor breakdown:
  - Piezoresistive accelerometer
  - 2 strain gauges
  - Resistor/mass
    - Voltage divider circuit
- High-speed camera

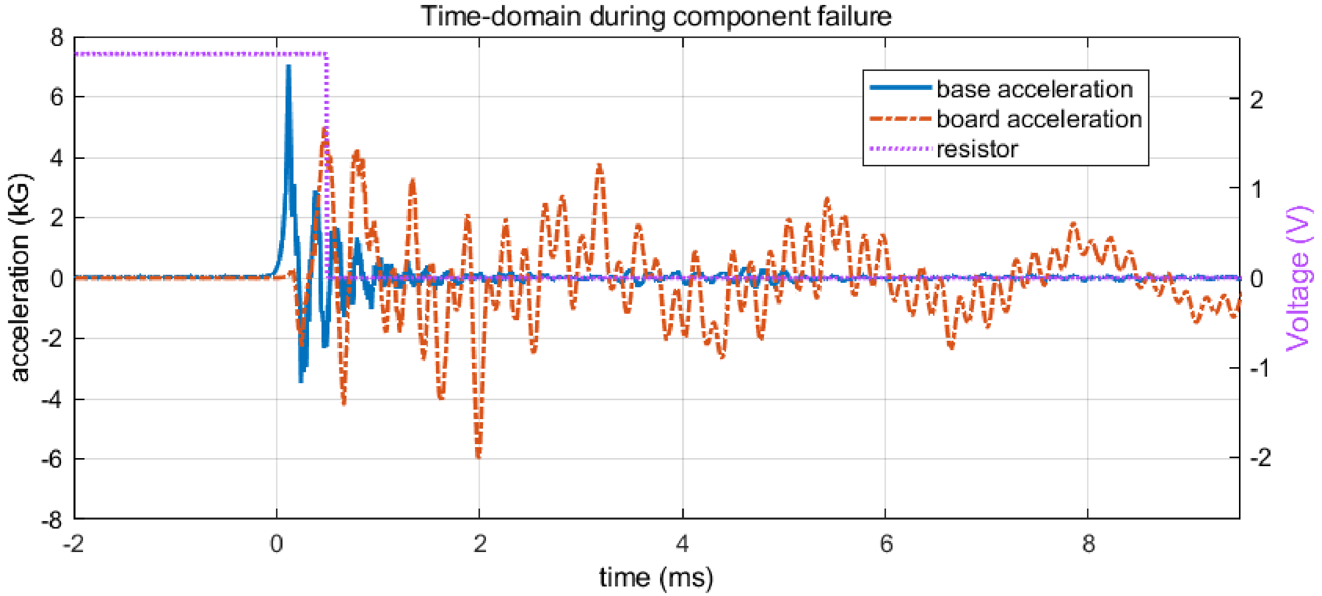


RESISTOR CIRCUIT

- Time reference for detachment
- Voltage divider
  - Continuous 2.5 V when attached
  - 0 V when detached



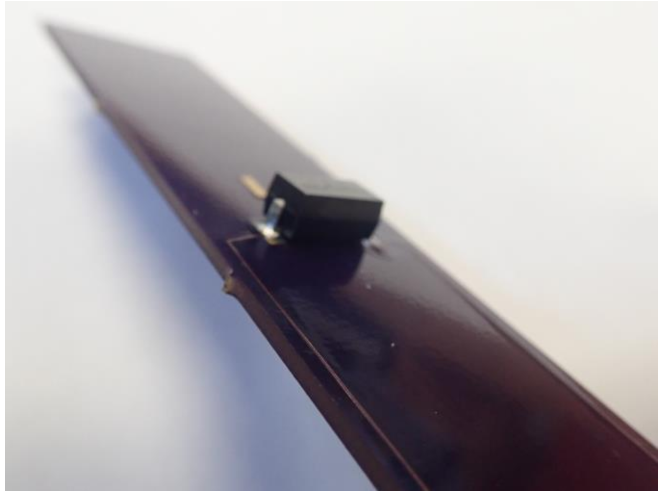


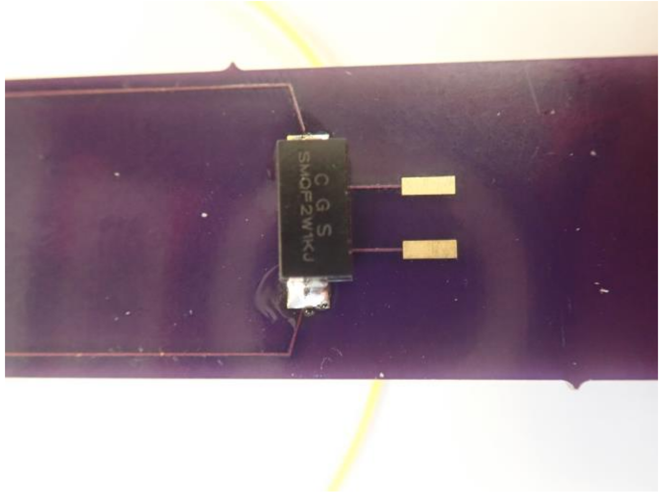


FINITE ELEMENT MODELING

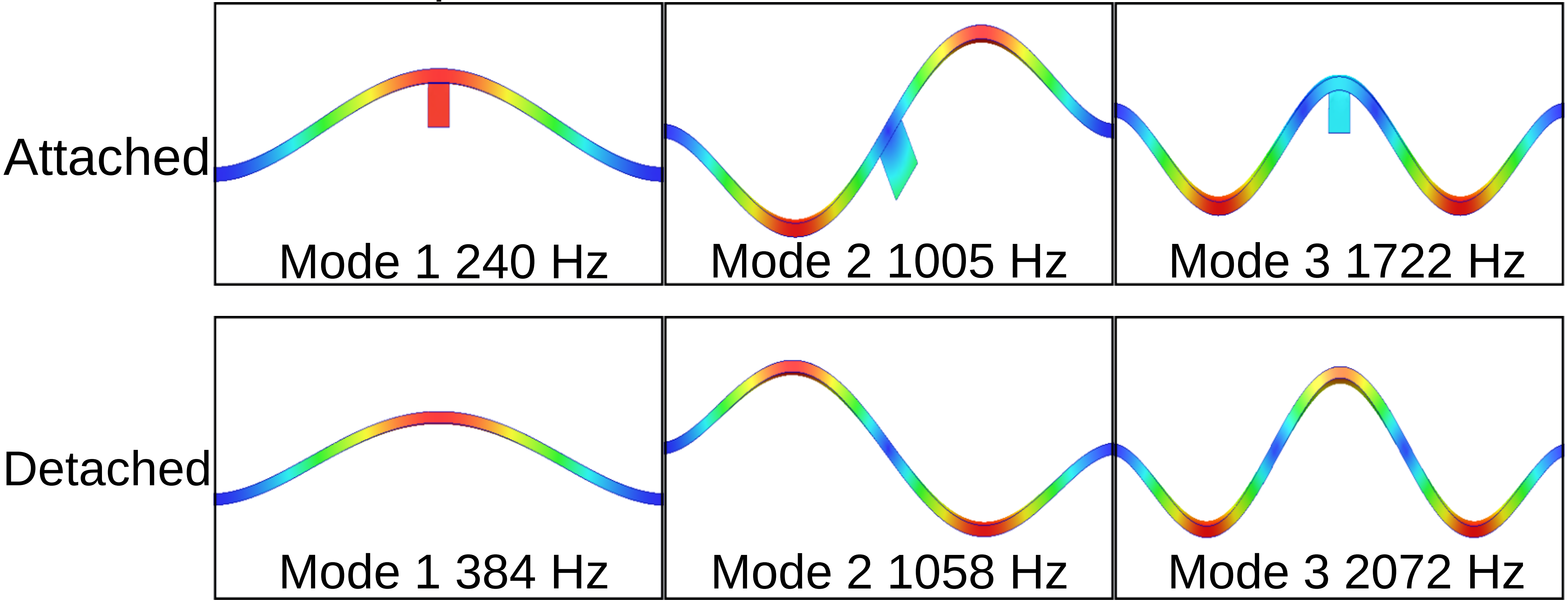
- Aimed to verify the expected trend:
  - Decreased mass will increase the natural frequency of the whole structure

Material	Density (lb/ft^3)	Young's Modulus (psi)	Poisson ratio
FR4	118.64	2,697,707	0.2



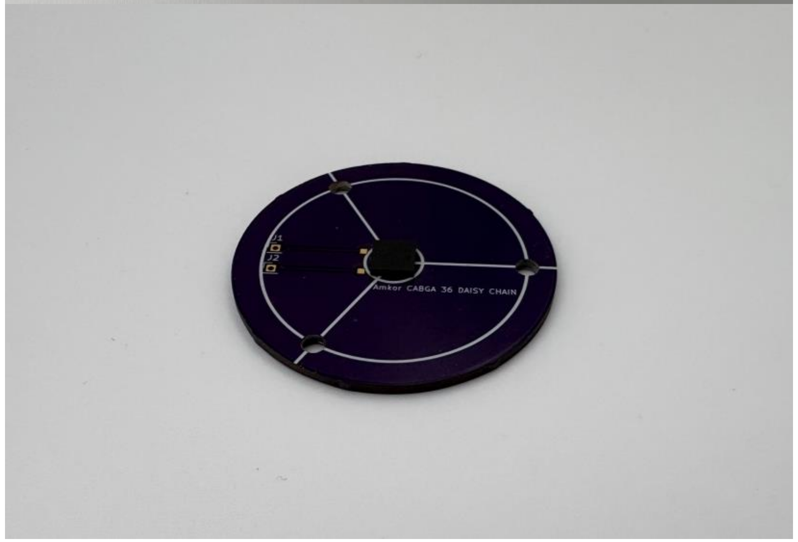


Component Attached vs Detached From a PCB

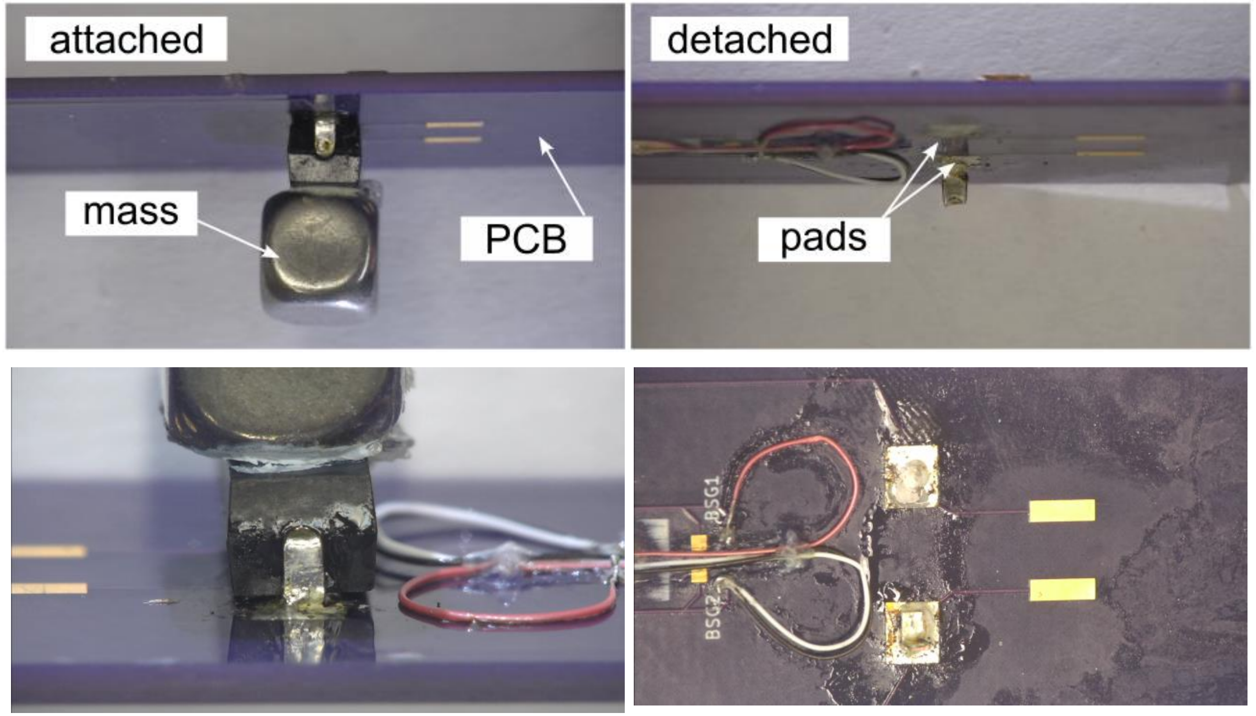


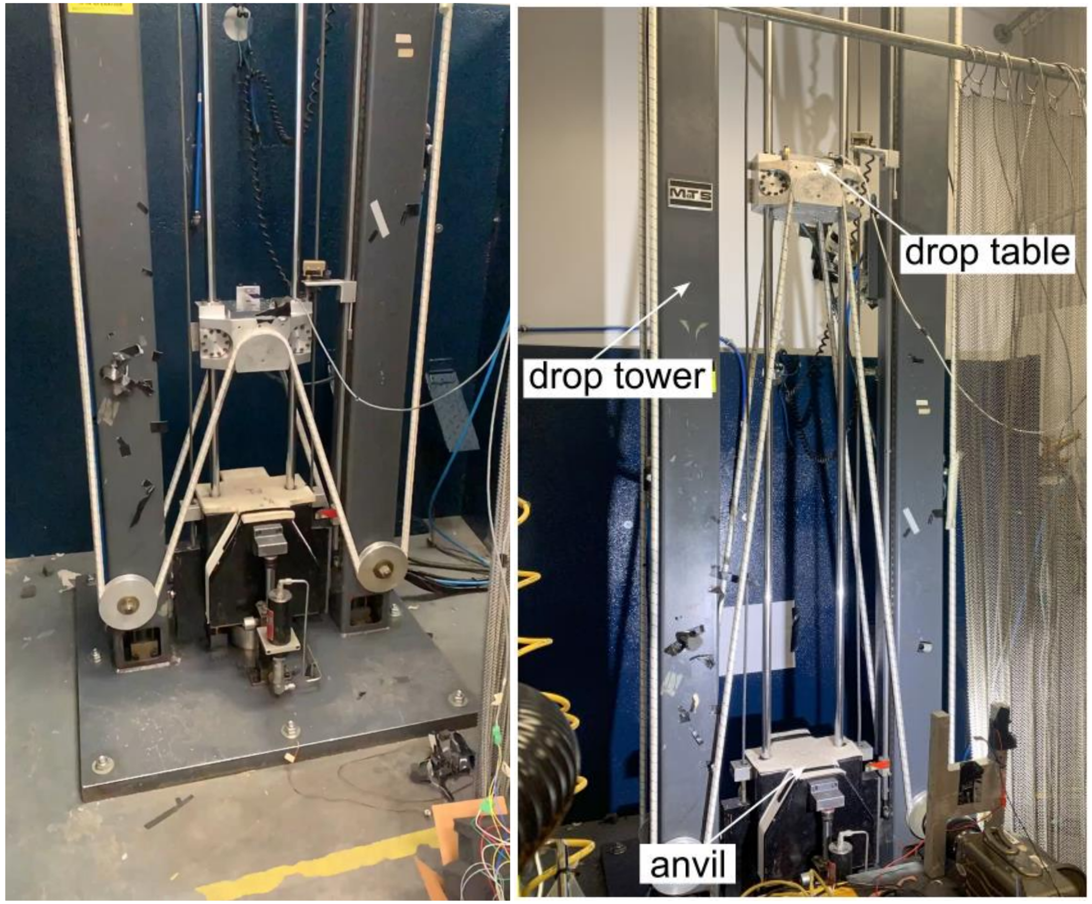
EDGE-PROCESSING METHODS

- Microcontroller-based
  - FFT computation
  - Peak detection on frequency components
  - Damage response and control
    - Damping vibrations using piezoelectric actuators
  - Reduce latency, autonomous, prolong lifespan
  - Need to consider
    - Computational power
    - Sampling rates
    - Algorithm optimization



EXPERIMENTAL APPROACH





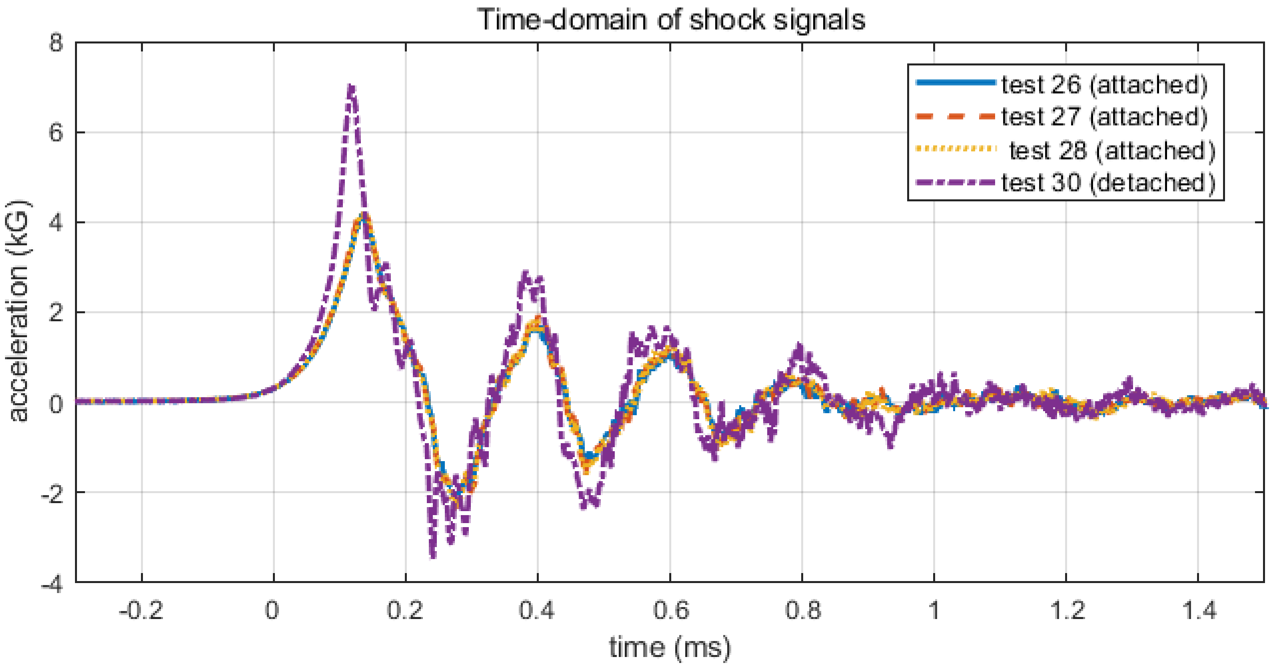
HIGH-RATE IMPACTS

Attached Test

Detached Test

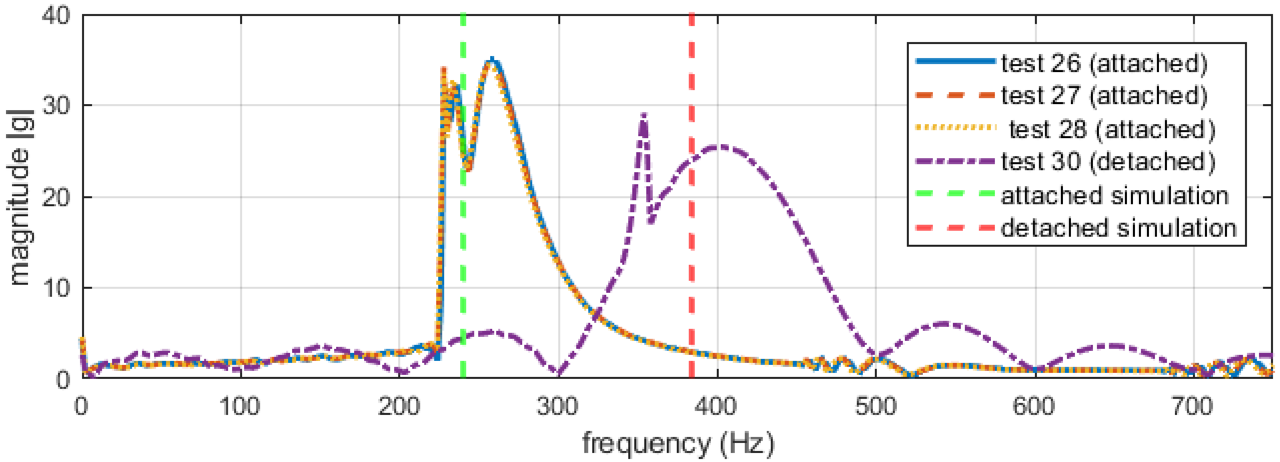
EXPERIMENTAL OUTCOMES

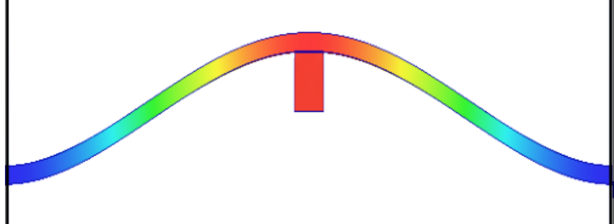
- Sequential tests show differences in measured acceleration
  - On a failure (detached) test, the system takes longer to dampen



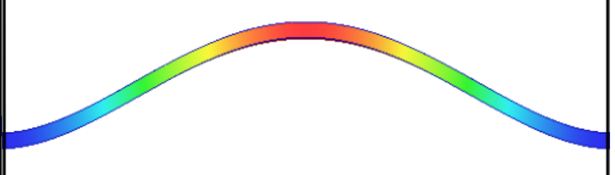
EXPERIMENTAL OUTCOMES

- Mode 1 frequencies
  - Resistor attached:
    - Simulated: 240 Hz
    - Tested: 258 Hz
    - 7.50% error
  - Resistor detached:
    - Simulated: 384 Hz
    - Tested: 354 Hz
    - 7.81% error





Mode 1 240 Hz

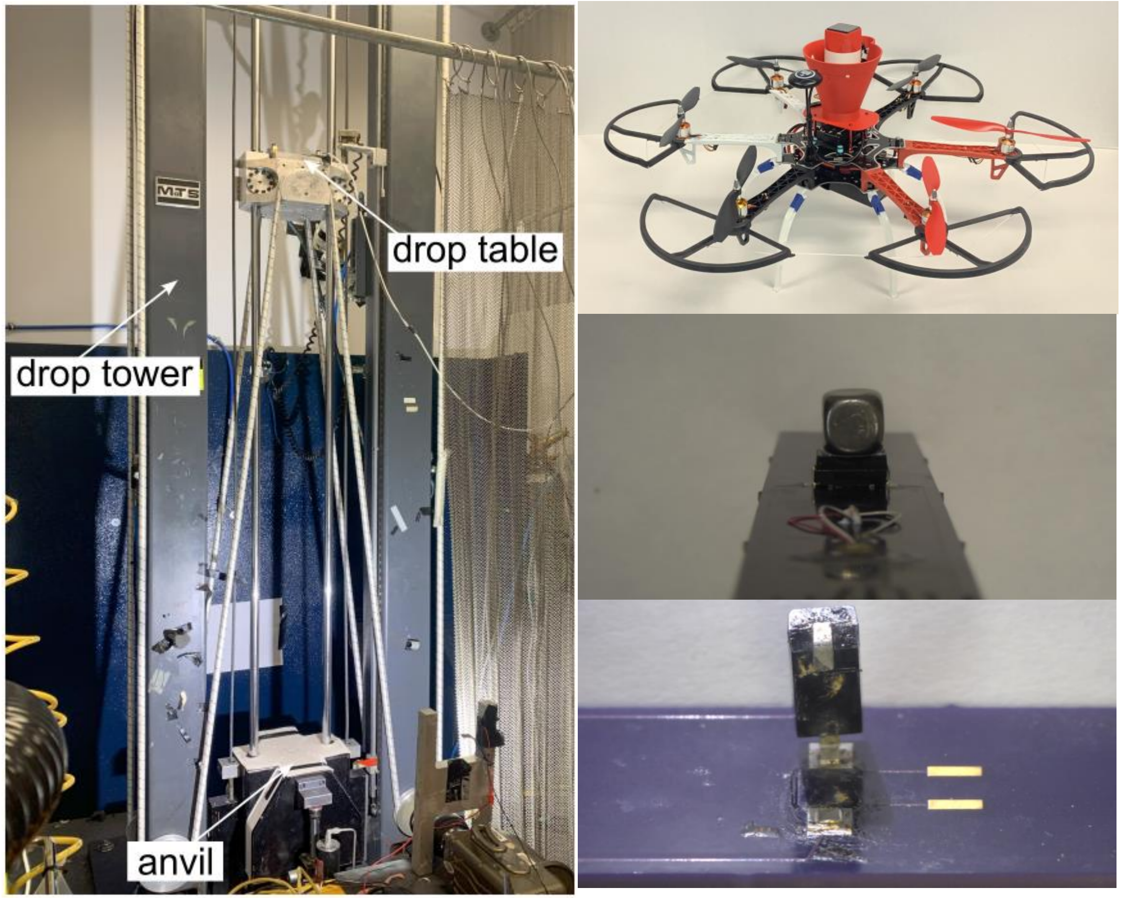


Mode 1 384 Hz

CONCLUSIONS AND FUTURE DIRECTIONS

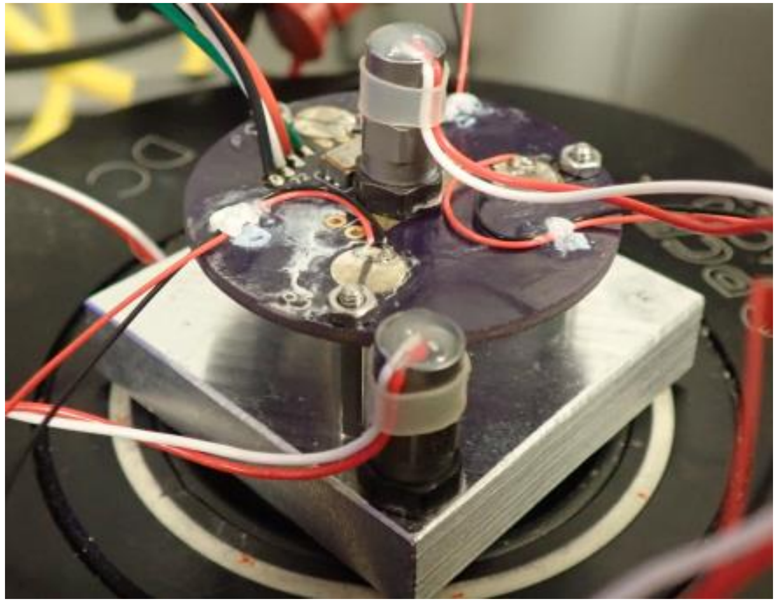
CONCLUSIONS

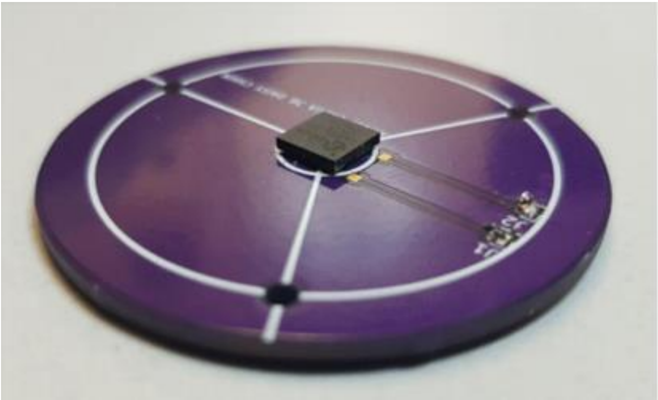
- Edge-computing and embedded sensors work well for rapid damage detection
- Onboard FFT computations closely match offline, high-precision results
- Systems like these can operate independently in the field
- This approach enables early warning mechanisms for structural health and dynamic shock environments



FUTURE DIRECTIONS

- Sensor Packages
  - Improve algorithm
  - Waystation for off-site data reading
- Electronic Assemblies
  - Implement edge processing
  - Controlled failure methods





ACKNOWLEDGMENT

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THANKS!
QUESTIONS?

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