# EXPERIMENTAL ANALYSIS TO ENABLE LOW-LATENCY STRUCTURAL HEALTH MONITORING FOR ELECTRONICS IN HIGH-RATE DYNAMIC ENVIRONMENTS

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# OUTLINE

- Background and Introduction
- Methodology
- Experimental approach
- Results
- Conclusions and future work

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# 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

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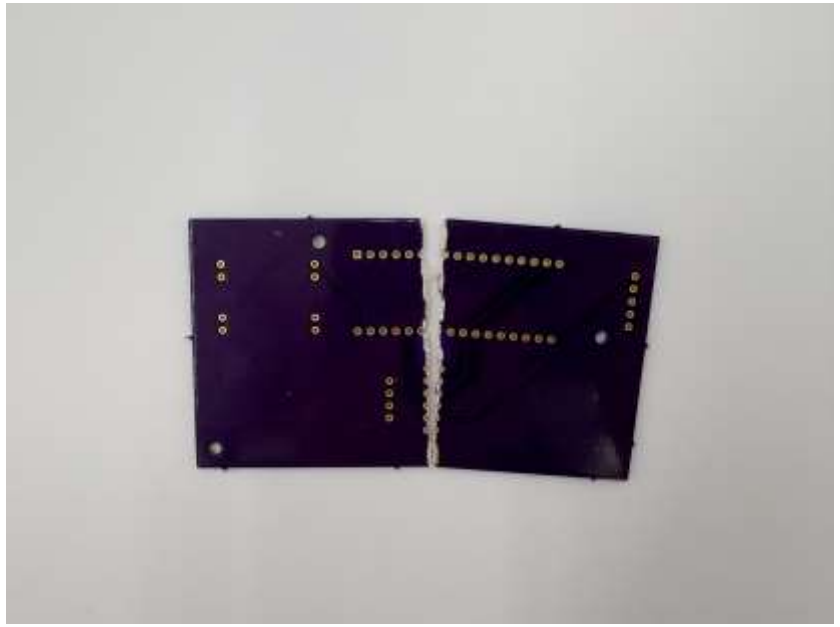
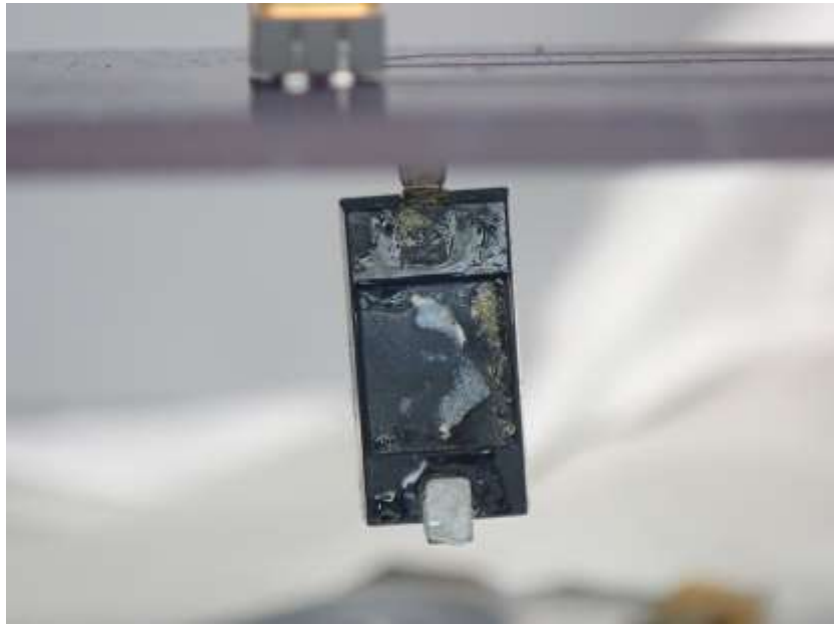
# INTRODUCTION

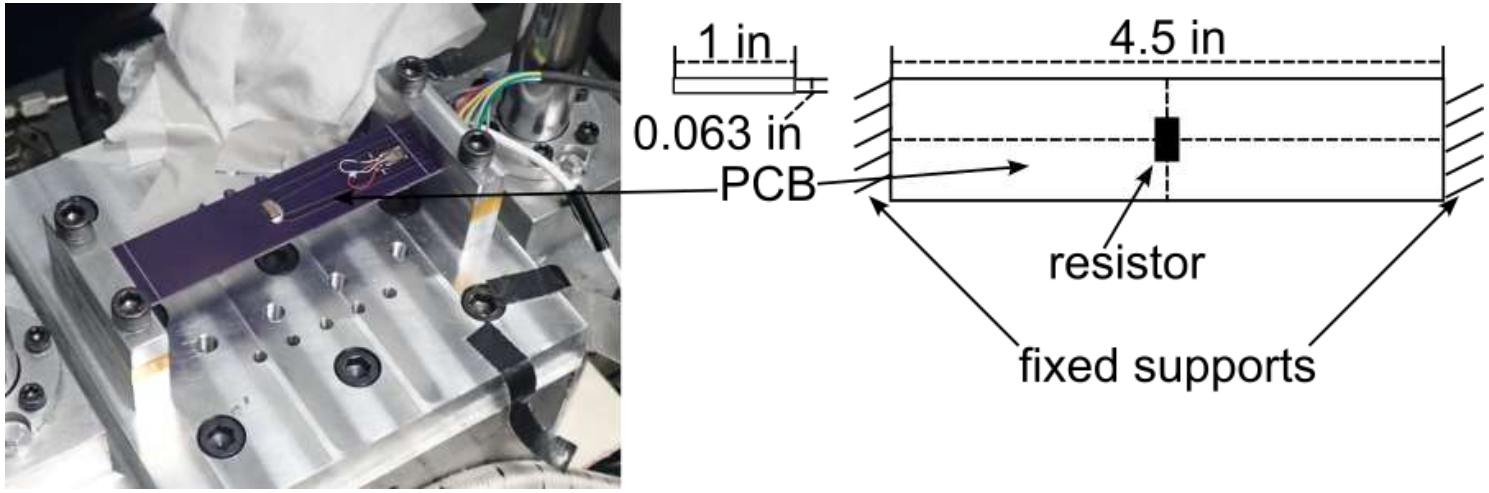
- Importance: Electronics in high-rate dynamic environments
- Problem: high-rate impacts can damage electronics, causing them to not function properly
- Proposal: Use embedded sensors and later combine them with an edge processor to detect damage
- Objective: Implement a frequency-based damage detection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

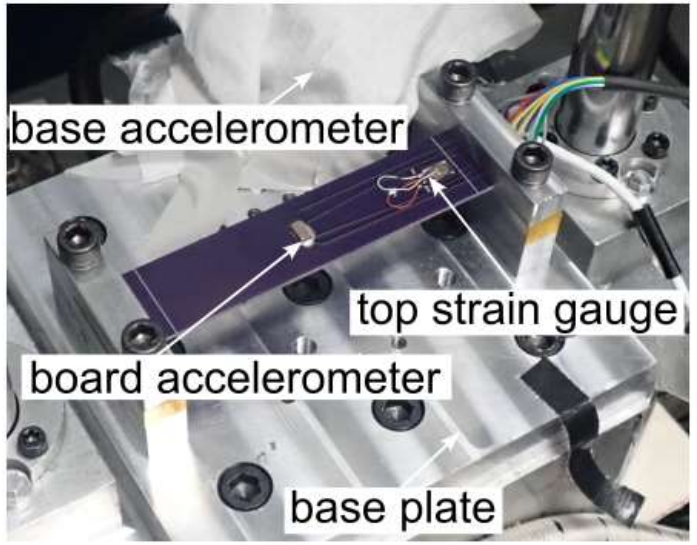


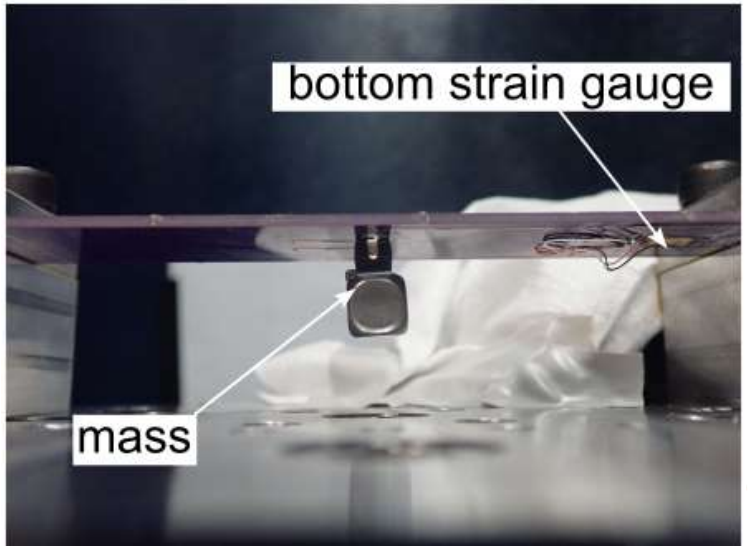


# METHODOLOGY

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

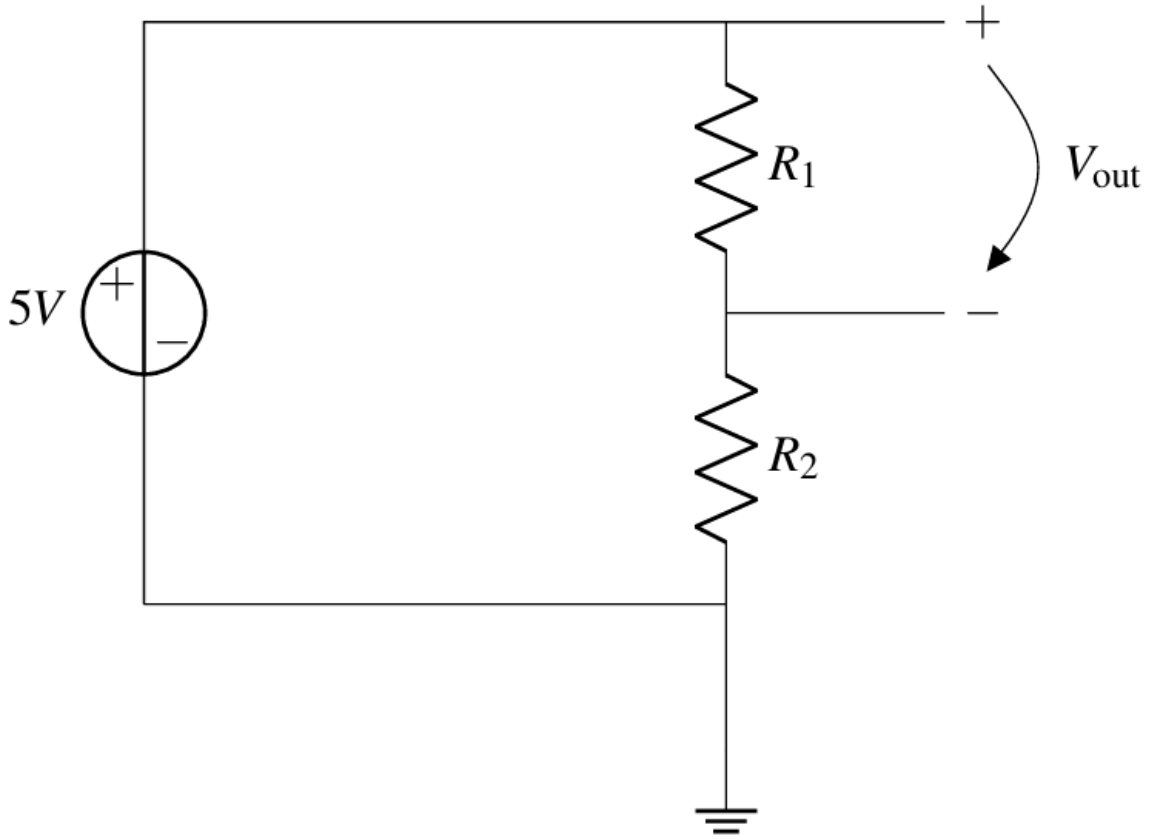


# METHODOLOGY

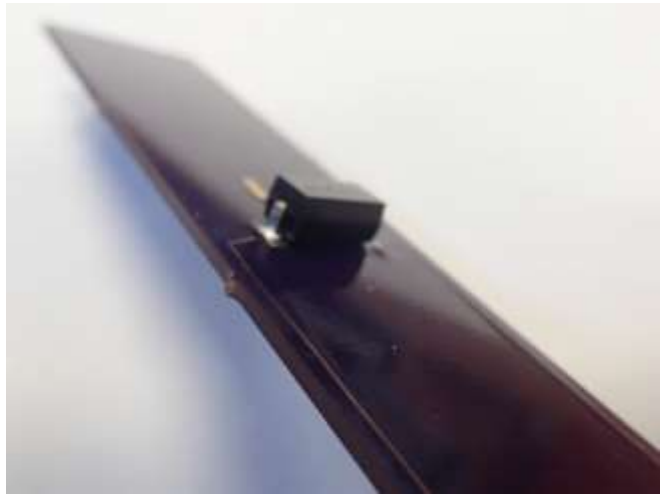
- Resistor circuit used to get a time reference on the exact moment of failure
  - Voltage divider keeps a 2.5 V signal until failure, which then drops to 0 V

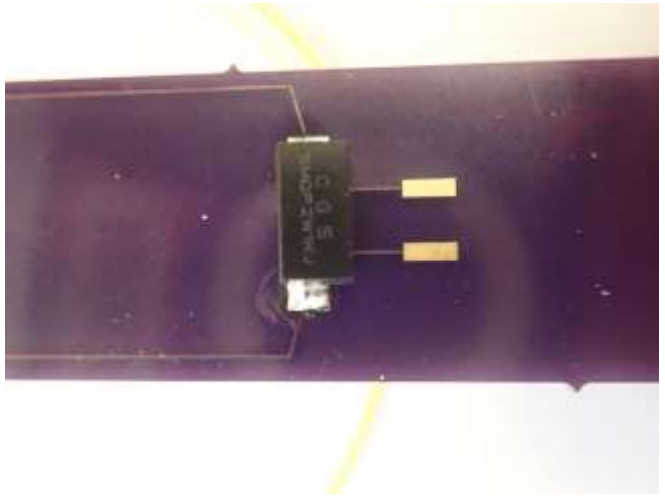


# METHODOLOGY

- Finite element simulations
  - To understand changes in vibrational modes due to the resistor falling off

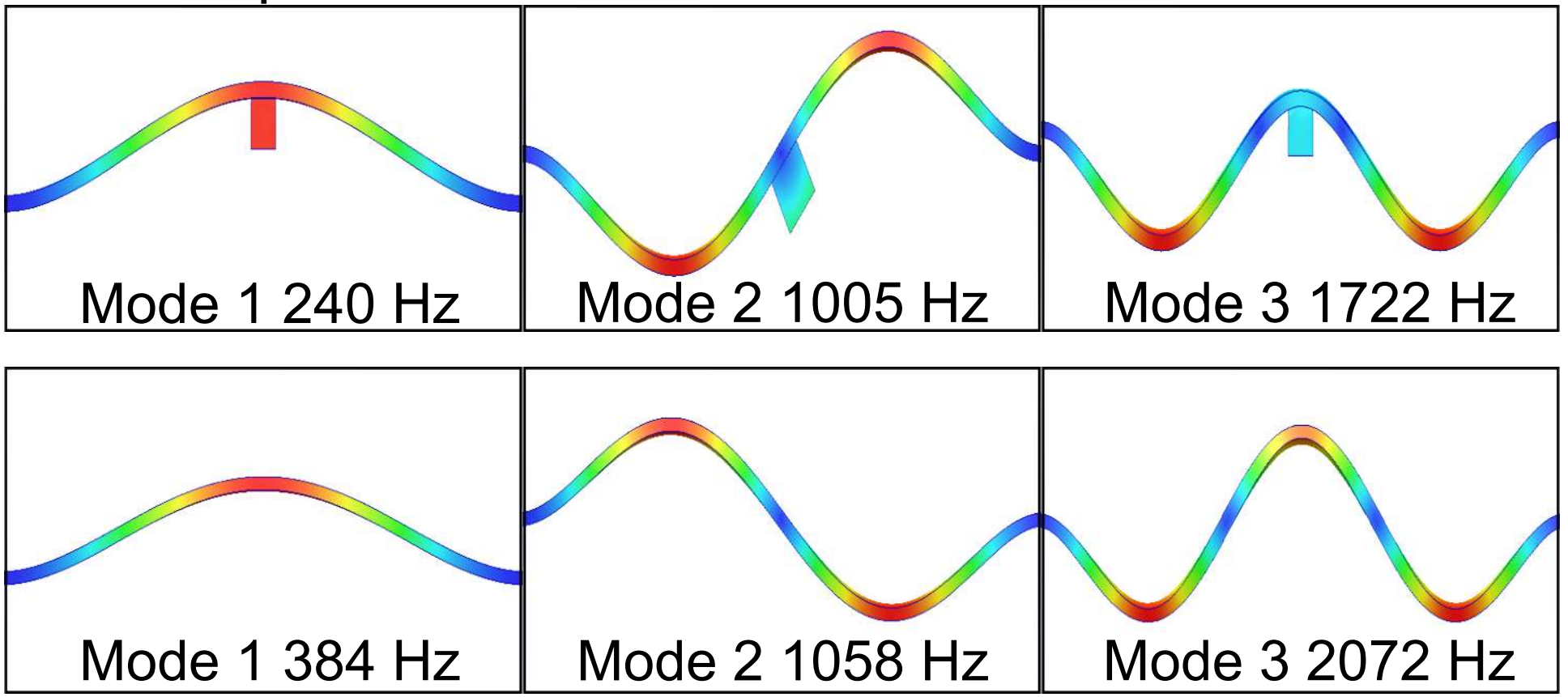
| Material | Density (lb/ft$^3$) | Young's Modulus (psi) | Poisson ratio |
|---|---|---|---|
| FR4 | 118.64 | 2,697,707 | 0.2 |





# METHODOLOGY

Component Attached vs Detached From a PCB

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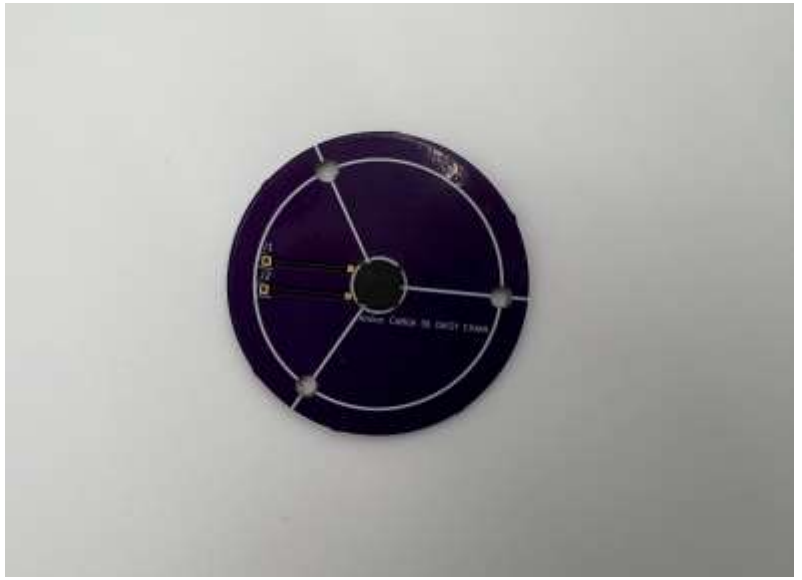
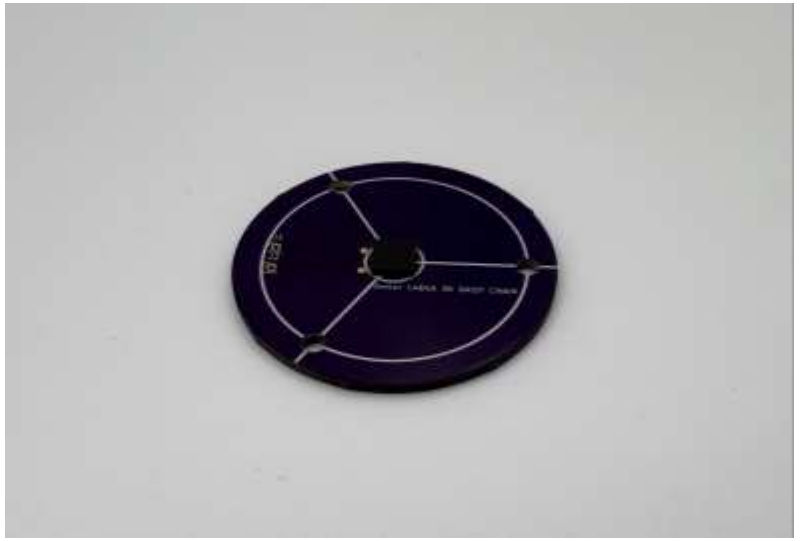
# METHODOLOGY

- Edge processing methods
  - Microcontroller-based
    - FFT computation
    - Peak detection on frequency components
      - Threshold-based
      - Pattern recognition
      - Adaptive filtering
    - Damage response and control
      - Damping vibrations using piezoelectric actuators





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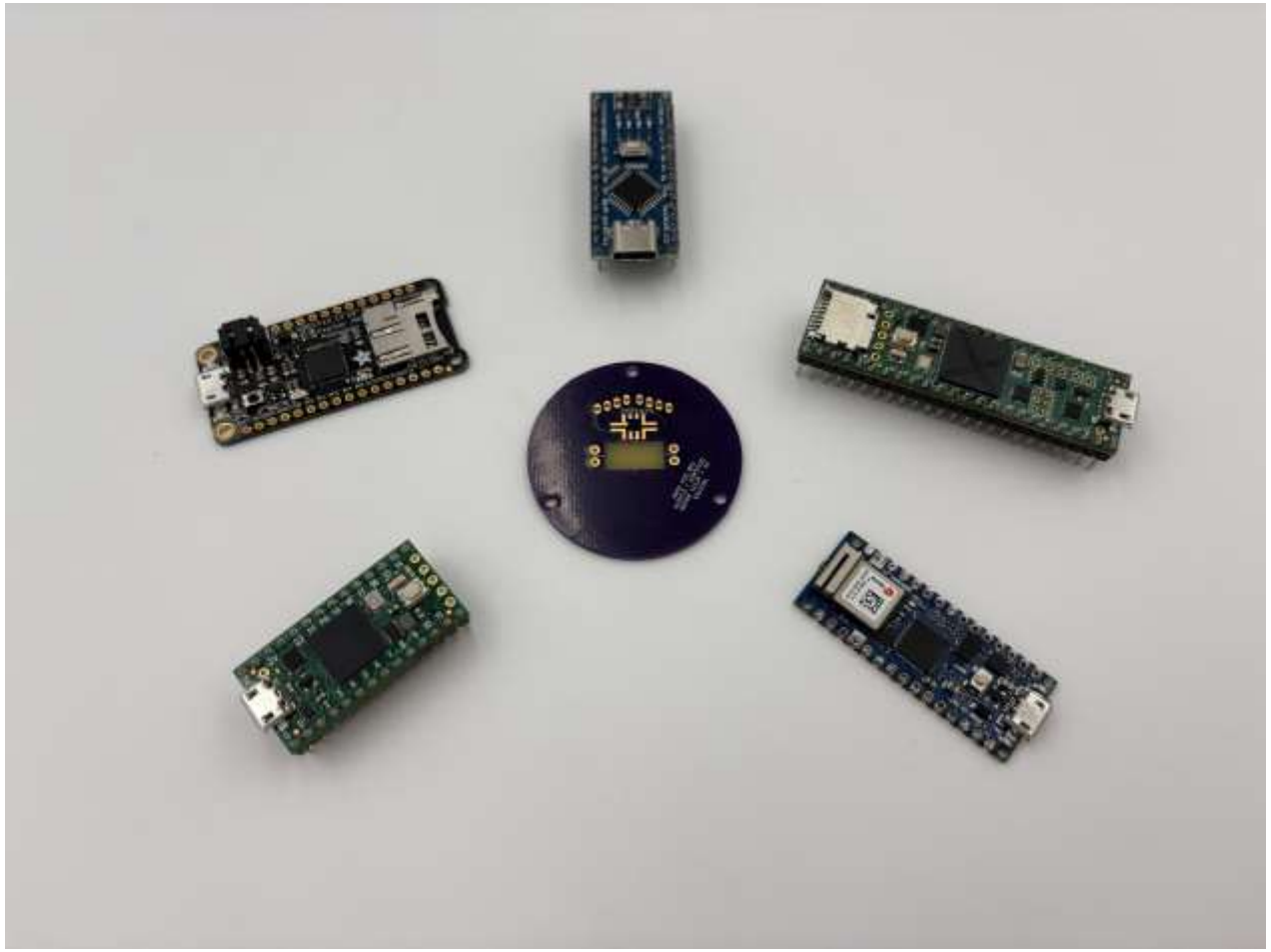
# METHODOLOGY

- Edge processing advantages
  - Reduces latency
  - Can operate autonomously
  - Prolong the lifespan of the PCBs
- Considerations
  - Controller with enough computational power and sampling rates
  - Optimization of algorithms for resource-constrained devices



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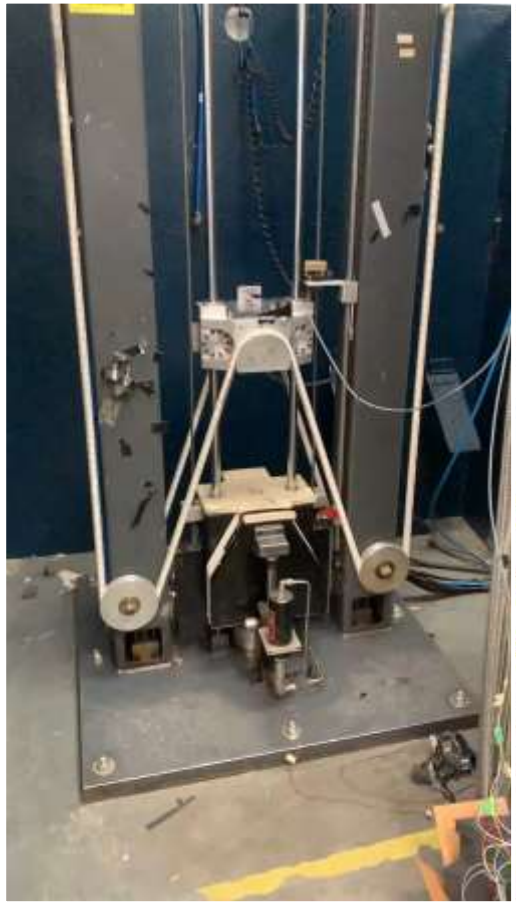
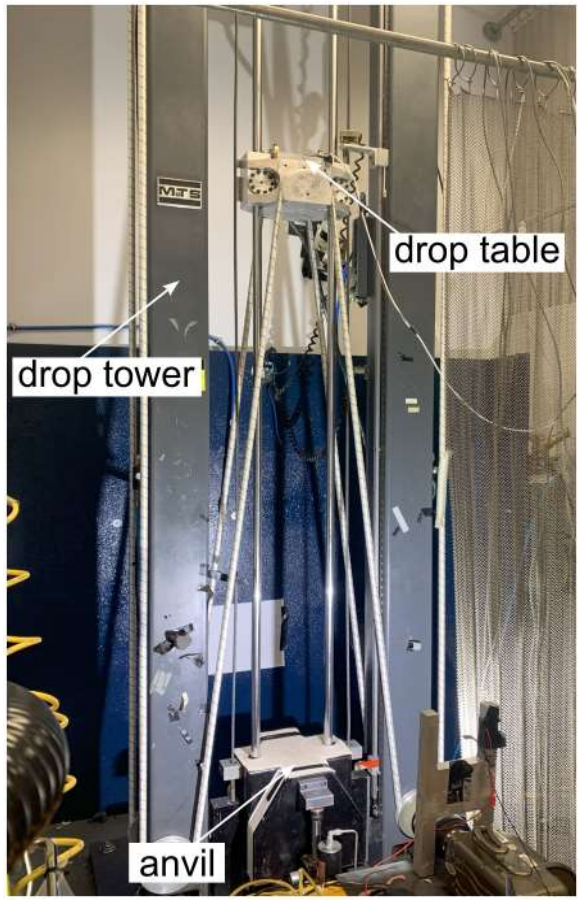
# EXPERIMENTAL APPROACH

- Drop tower (simulates high-rate impacts)
- Fixed-fixed printed circuit board with sensors
- Resistor/mass component meant to exaggerate the change in dynamics
- Several impacts at varying heights
- Intended to fail the resistor/mass and measure the differences in the response





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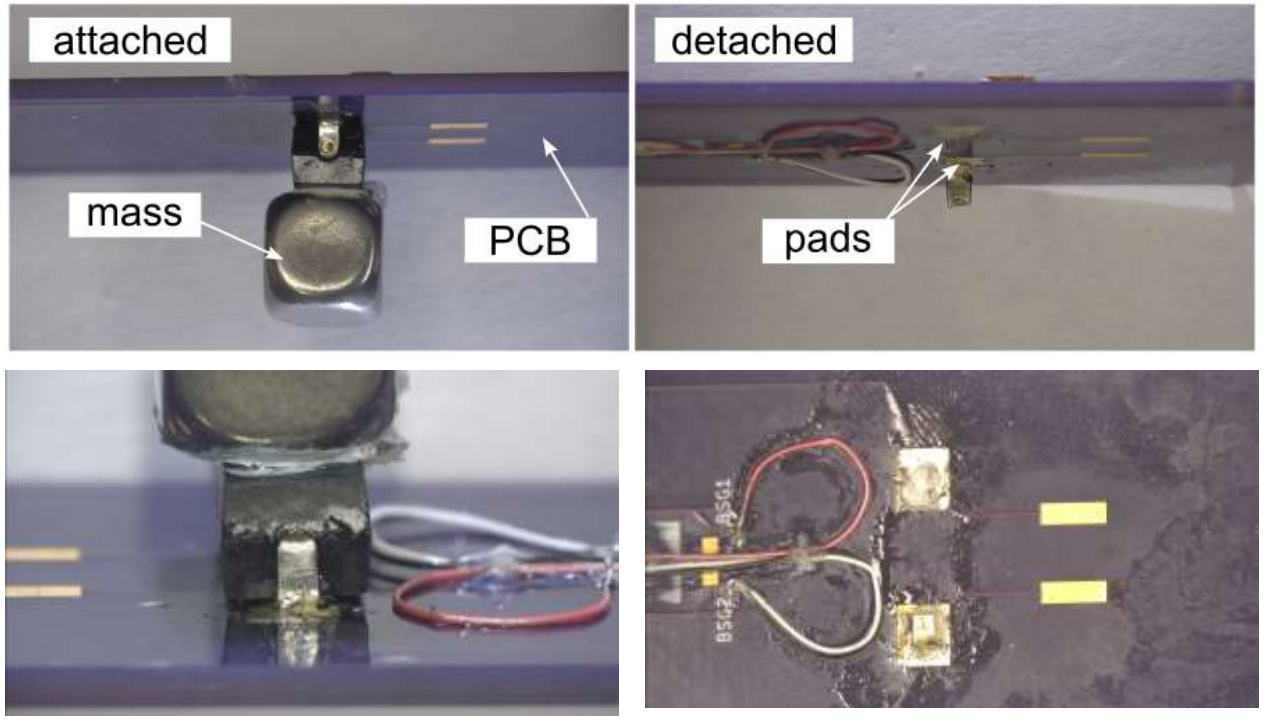

# EXPERIMENTAL APPROACH

Attached Test

Detached Test

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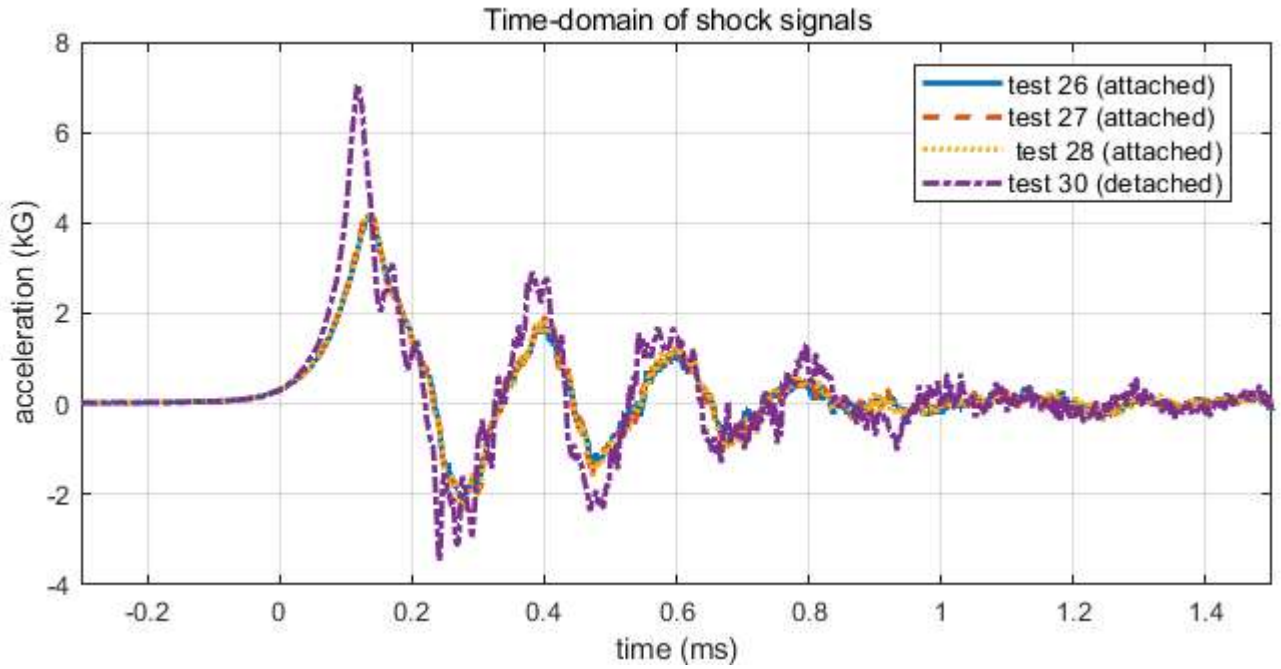
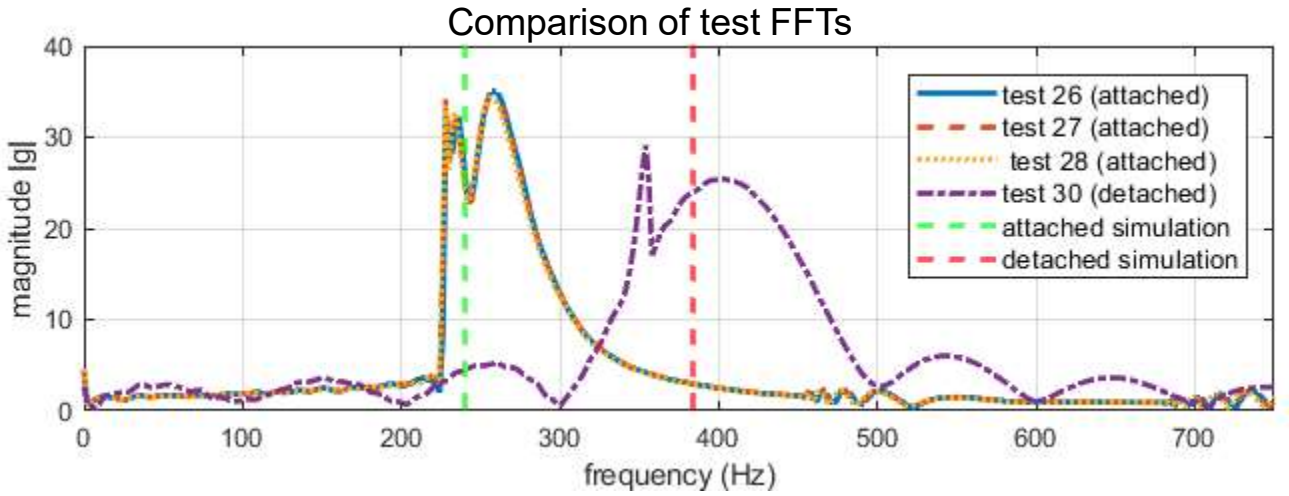
# RESULTS

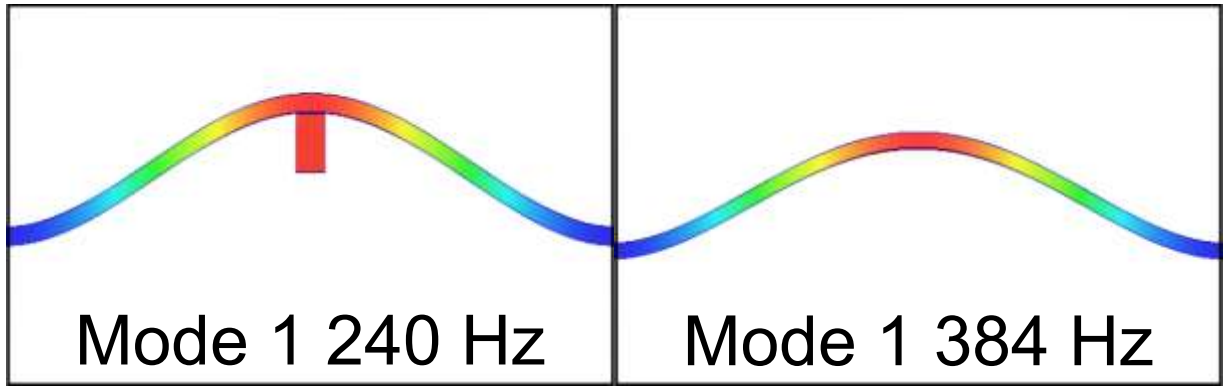
- Sequential tests show differences in measured acceleration
  - On a failure (detached) test, the system takes longer to dampen



# RESULTS

- 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

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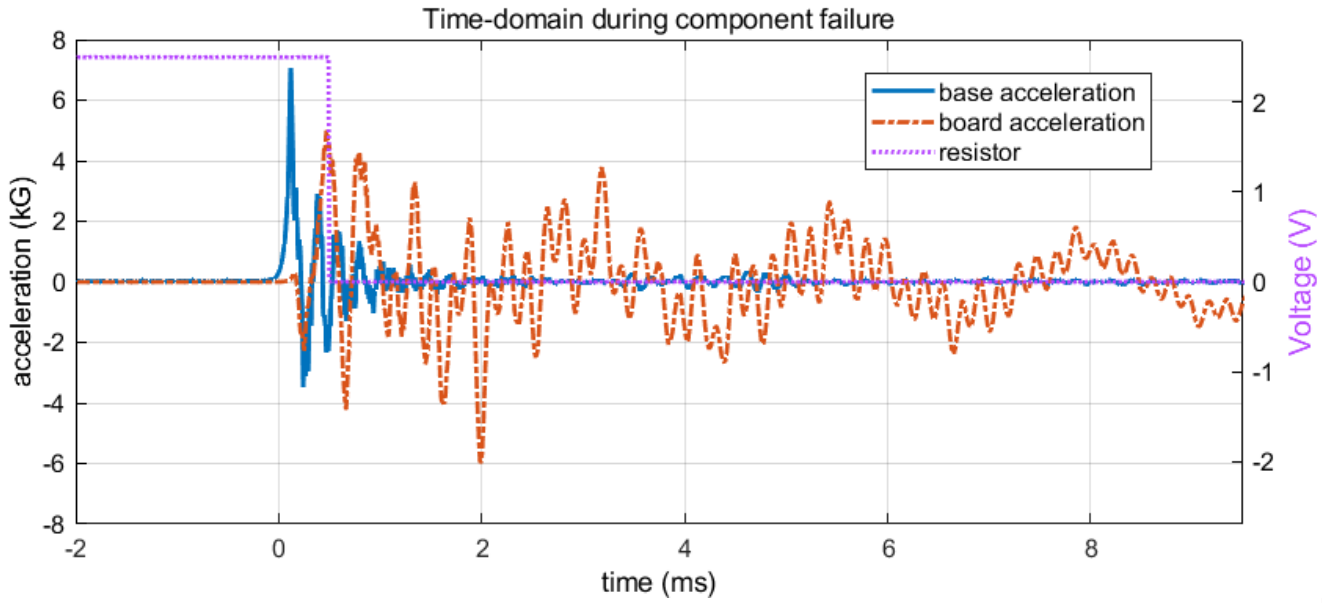
# CONCLUSIONS AND FUTURE WORK

- Viable solution for damage detection
- Future work:
  - Implement edge processing approach
  - Work on controlled methods to make failure more direct



# ACKNOWLEDGMENT

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# THANKS!

## Open-source Data Set

https://github.com/High-Rate-SHM-Working-Group/Dataset-9-repeated-impact-testing-of-rectangular-electronic-assembly

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# REFERENCES


- [1] Lalanne, C. Mechanical Shock. CRC Press, 1st edition (2002)
- [2] Dodson, J., Downey, A., Laflamme, S., Todd, M.D., Moura, A.G., Wang, Y., Mao, Z., Avitabile, P., and Blasch, E. High Rate Structural Health Monitoring and Prognostics: An Overview, pages 213–217. Springer International Publishing (2021)
- [3] Song, Z.G., Li, F.M., and Zhang, W. “Active flutter and aerothermal postbuckling control for nonlinear composite lami nated panels in supersonic airflow”. Journal of Intelligent Material Systems and Structures, 26(7):840–857 (2014)
- [4] Chomette, B., Chesn´e, S., R´ emond, D., and Gaudiller, L. “Damage reduction of on-board structures using piezoelectric components and active modal control—application to a printed circuit board”. Mechanical Systems and Signal Processing, 24(2):352–364 (2010)
- [5] Downey, A. and Micheli, L. “Vibration mechanics: A practical introduction for mechanical, civil, and aerospace engi neers” (2024)
- [6] HealthMonitoringofPCB’sUnderMechanicalShockLoads, volumeASME2019InternationalTechnicalConferenceand Exhibition on Packaging and Integration of Electronic and Photonic Microsystems of International Electronic Packaging Technical Conference and Exhibition (2019)
- [7] Jalink, J., Roucou, R., Zaal, J.J.M., Lesventes, J., and Rongen, R.T.H. “Effect of pcb and package type on board level vibration using vibrational spectrum analysis”. In 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), pages 470–475 (2017)
- [8] Yount, R., Satme, J.N., Wamai, D., and Downey, A.R.J. “Edge processing for frequency identification on drone-deployed structural health monitoring sensor nodes”. In Muench, P.L., Nguyen, H.G., and Diltz, R., editors, Unmanned Systems Technology XXVI, page 25. SPIE (2024)
- [9] Sharma, G., Mishra, A., and Selvaraj, P. “Dynamic analysis of fixed-fixed beam under mechanical shock loads”. IOP Conference Series: Materials Science and Engineering, 998(1):012019 (2020)
- [10] Worden, K., Farrar, C.R., Manson, G., and Park, G. “The fundamental axioms of structural health monitoring”. Proceed ings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 463(2082):1639–1664 (2007)
- [11] Aytekin, B. “Vibration analysis of pcbs and electronic components”. Master’s thesis, Middle East Technical University (2008)
- [12] Kabir, E., Coble, D., Satme, J.N., Downey, A.R., Bakos, J.D., Andrews, D., and Huang, M. “Accelerating lstm-based high rate dynamic system models”. In 2023 33rd International Conference on Field-Programmable Logic and Applications (FPL), volume 10, pages 327–332. IEEE (2023)
- [13] Wang, X., Han, Y., Leung, V.C.M., Niyato, D., Yan, X., and Chen, X. Fundamentals of Edge Computing, pages 15–32. Springer Singapore, Singapore (2020)
- [14] Krishnasamy, E., Varrette, S., and Mucciardi, M. “Edge computing: An overview of framework and applications”. Tech nical report (December 2020) https://prace-ri.eu/wp-content/uploads/Edge-Computing-An-Overview-of-Framework-and Applications.pdf.
- [15] Yount, R., Dodson, J., and Moura, A. “Dataset 9 repeated impact testing of rectangular electronic assembly”.


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