Online Health Monitoring of Electronic Components Subjected to Repeated High-energy Shock

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Methodology | Experimentation | Results and Discussion | Future work

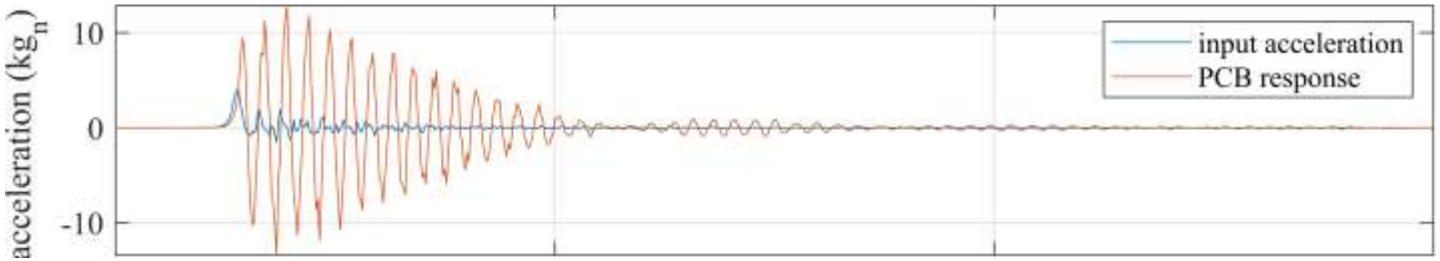
Outline:

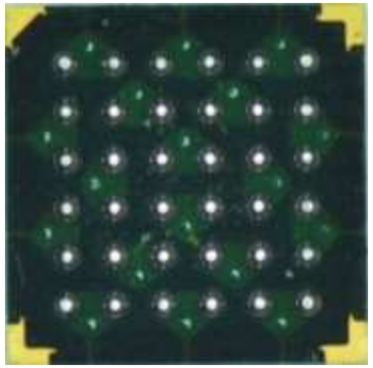
Methodology
- PCB failure mechanisms
- LSTM state estimators

Experimentation
- Experimental system
- Experimental procedure
- Validation and feature extraction
- Model development and deployment

Results and discussion
- Model performance
- FPGA implementation
- Timing and recourse utilization

Future work
- Multi-connection impedance measurement
- Reduce latency and maximize model performance

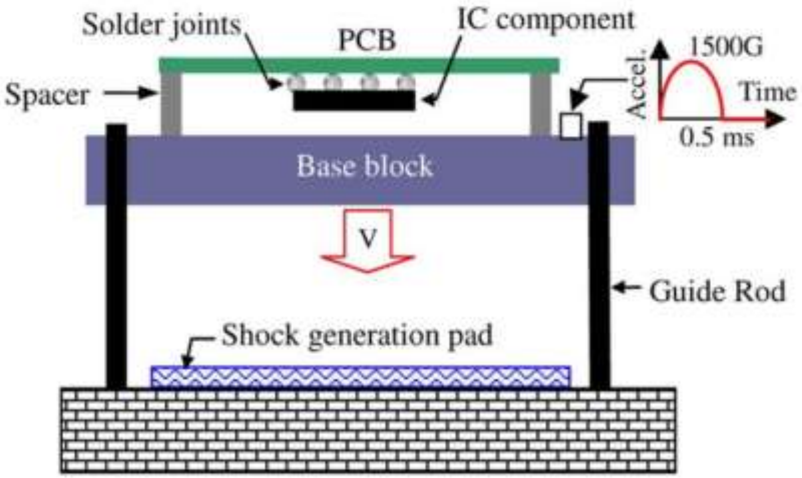




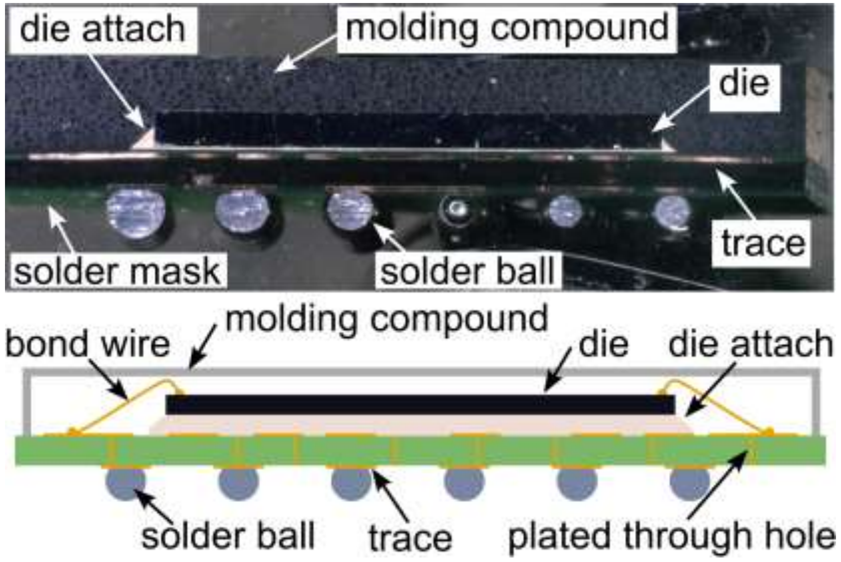
PCB failure mechanisms under shock

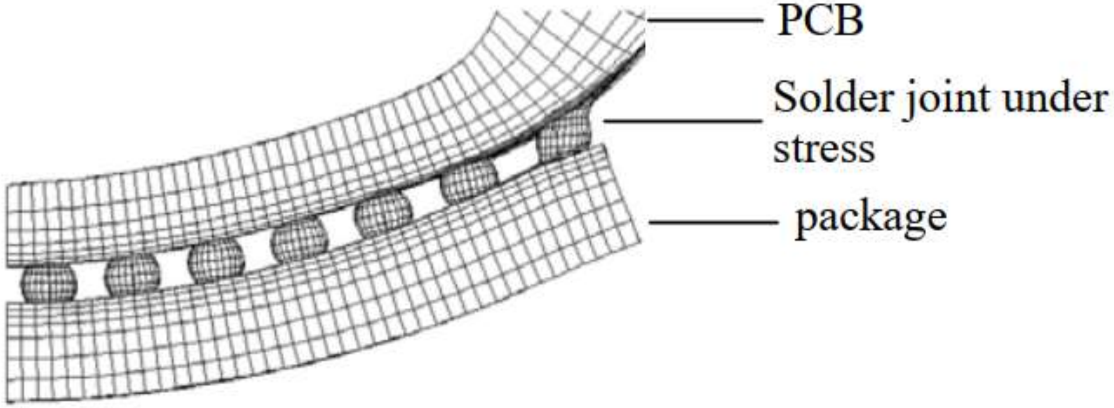
PCB failures under shock are caused by:

- 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.



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.



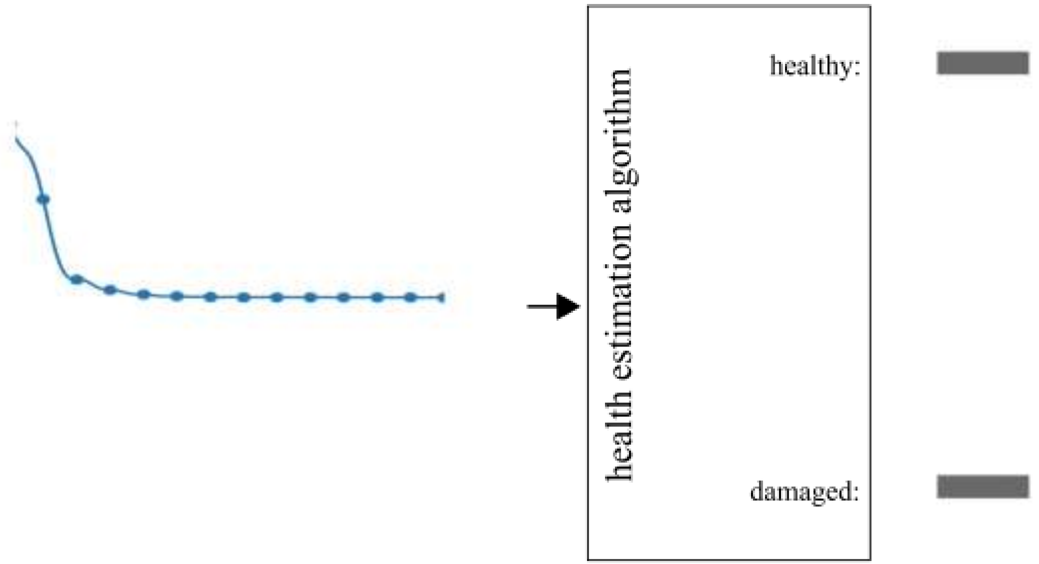


Seah, S. K. W., Wong, E. H., Ranjan, R., Lim, C. T., and Mai, Y. W., 2005, "Understanding and testing for drop impact failure," ASME Pacific Rim Technical Conference and Exhibition on Integration and Packaging of MEMS, NEMS, and Electronic Systems, pp. 1089-1094.

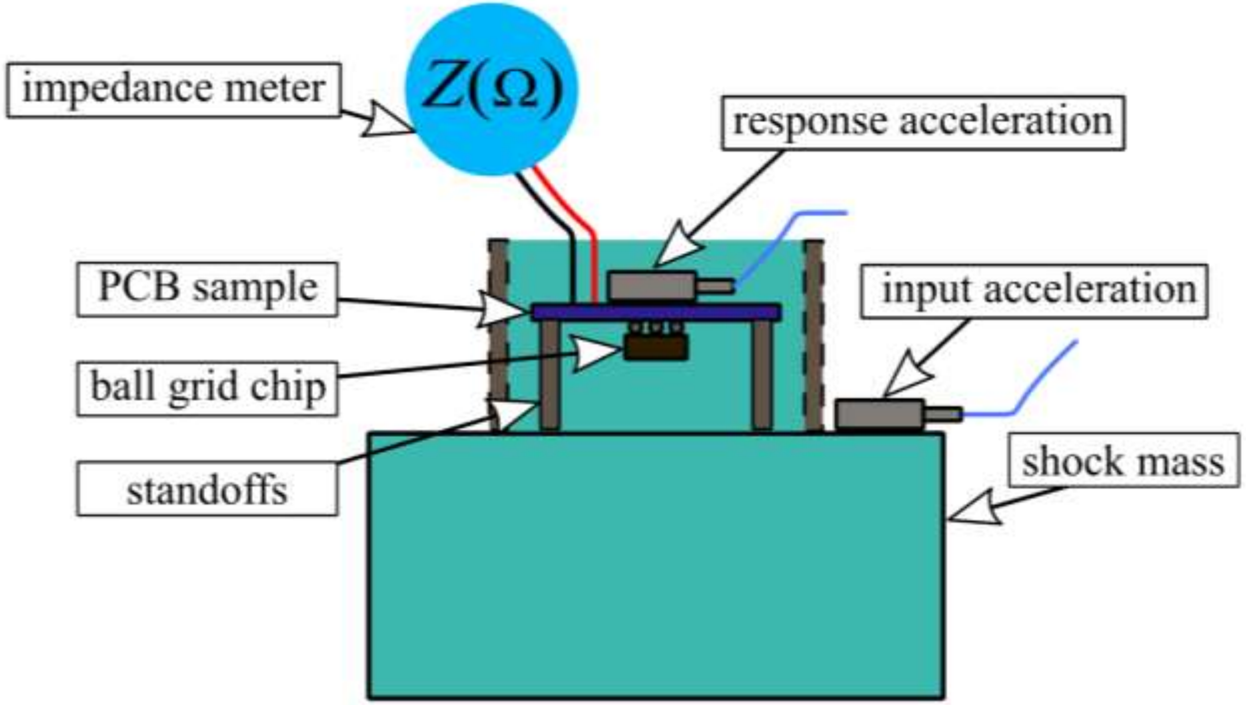
Long short-term memory state estimators

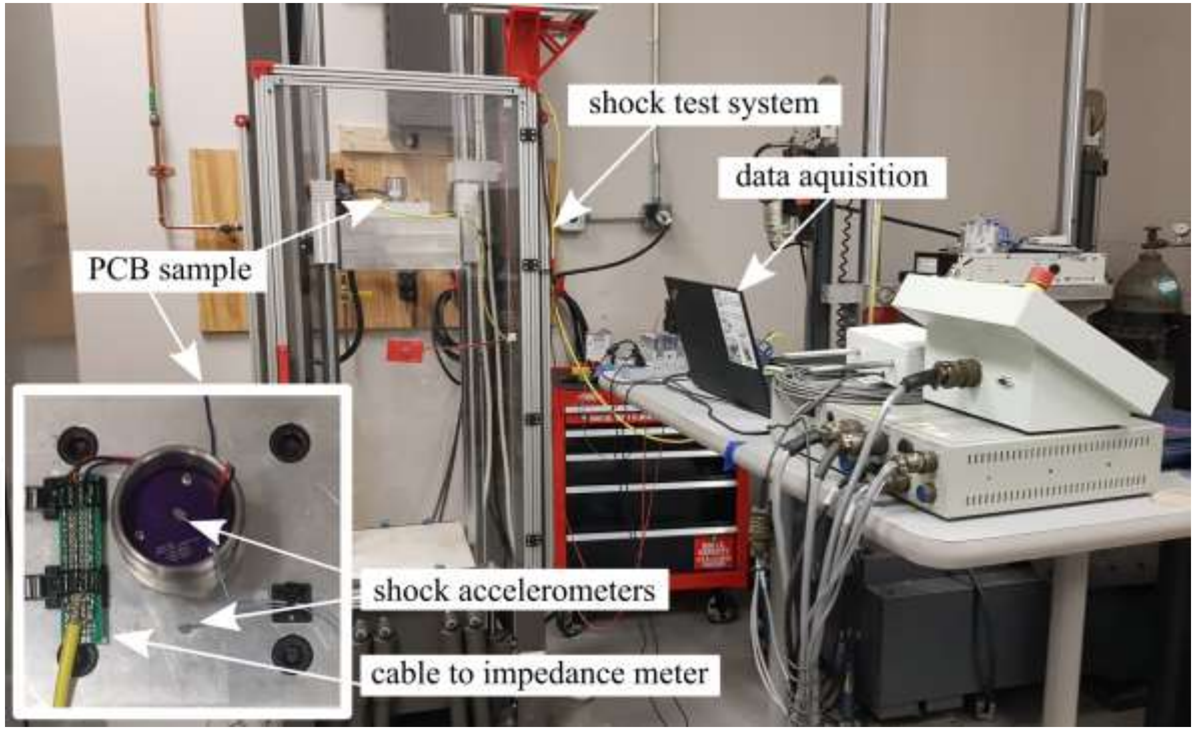
- Type of recurrent neural networks
- Using feedback to pass state information to future timesteps
- Data enters the network as a singleton vector
- Internal states of the network are updated
- The network then produces an output
- The output is fed into a dense layer to make a prediction

$$f_t = \sigma(W_f x_t + U_f h_{t-1} + b_f)$$
$$i_t = \sigma(W_i x_t + U_i h_{t-1} + b_i)$$
$$o_t = \sigma(W_o x_t + U_o h_{t-1} + b_o)$$
$$\tilde{c}_t = \tanh(W_c x_t + U_c h_{t-1} + b_c)$$
$$c_t = f_t \circ c_{t-1} + i_t \circ \tilde{c}_t$$
$$h_t = o_t \circ \tanh(c_t)$$
$$y_t = W_d^T h_t + b_d$$

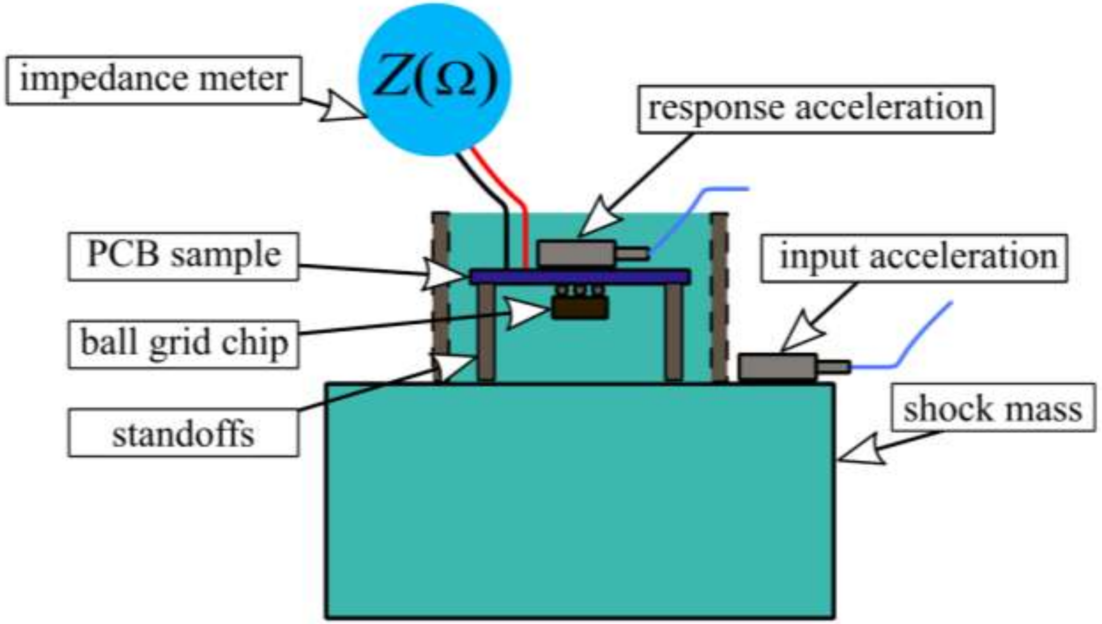


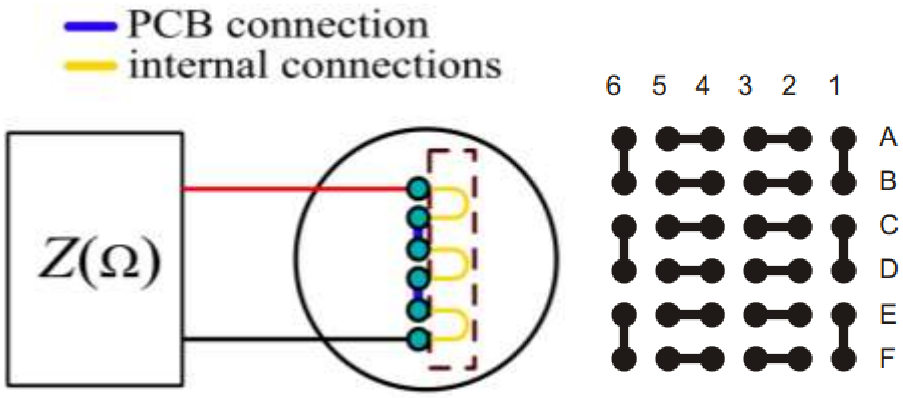
Experimental system

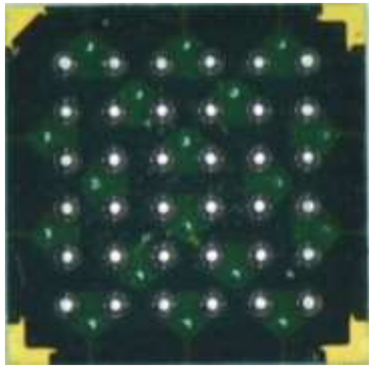


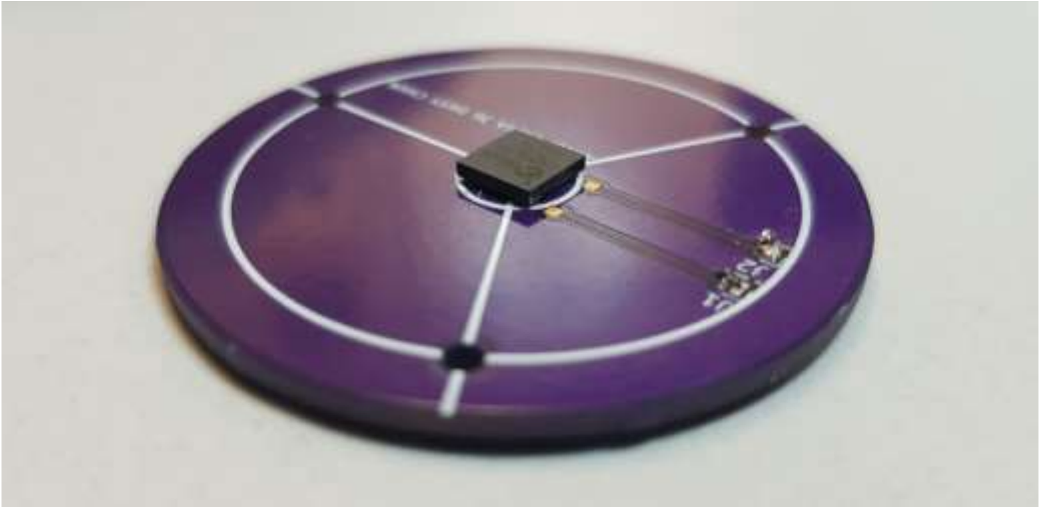


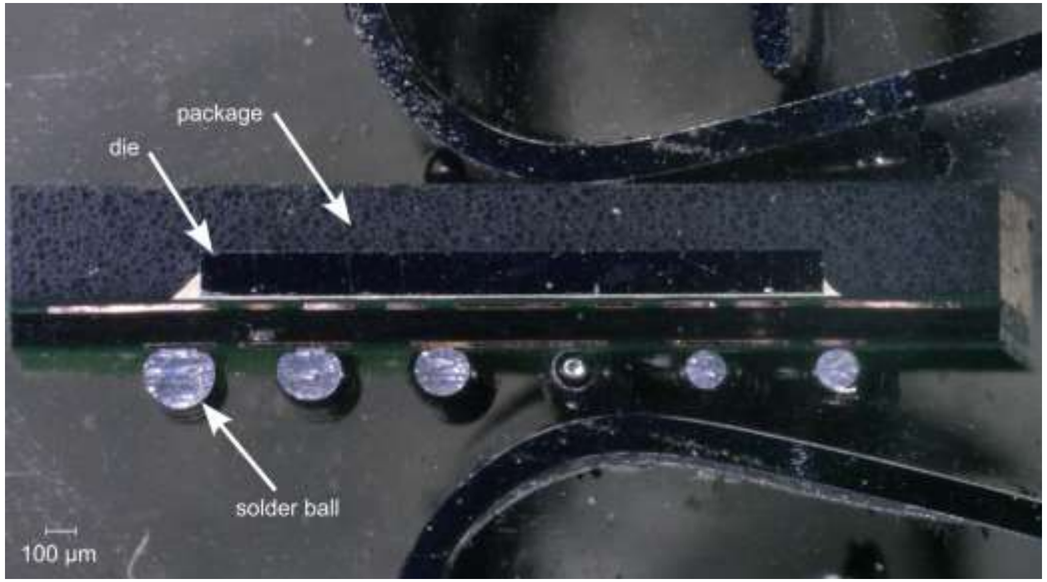
Experimental system



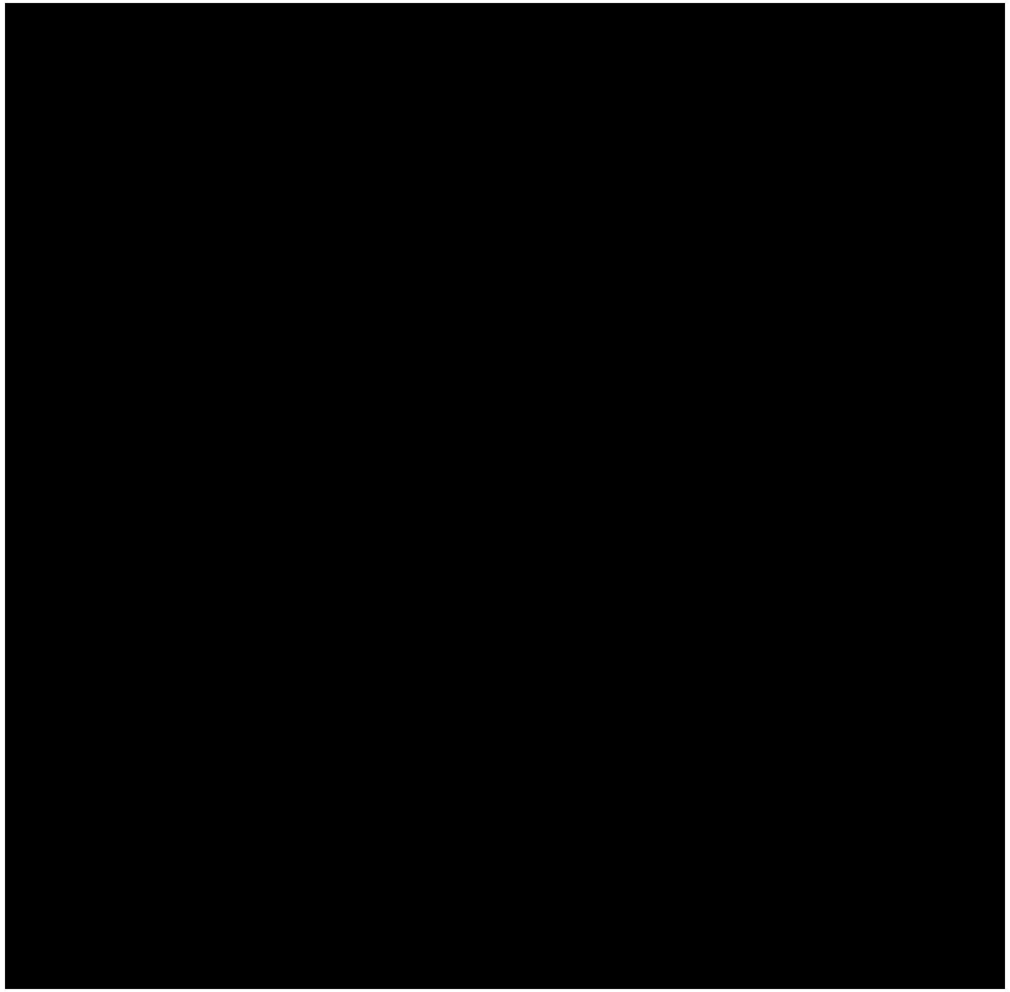


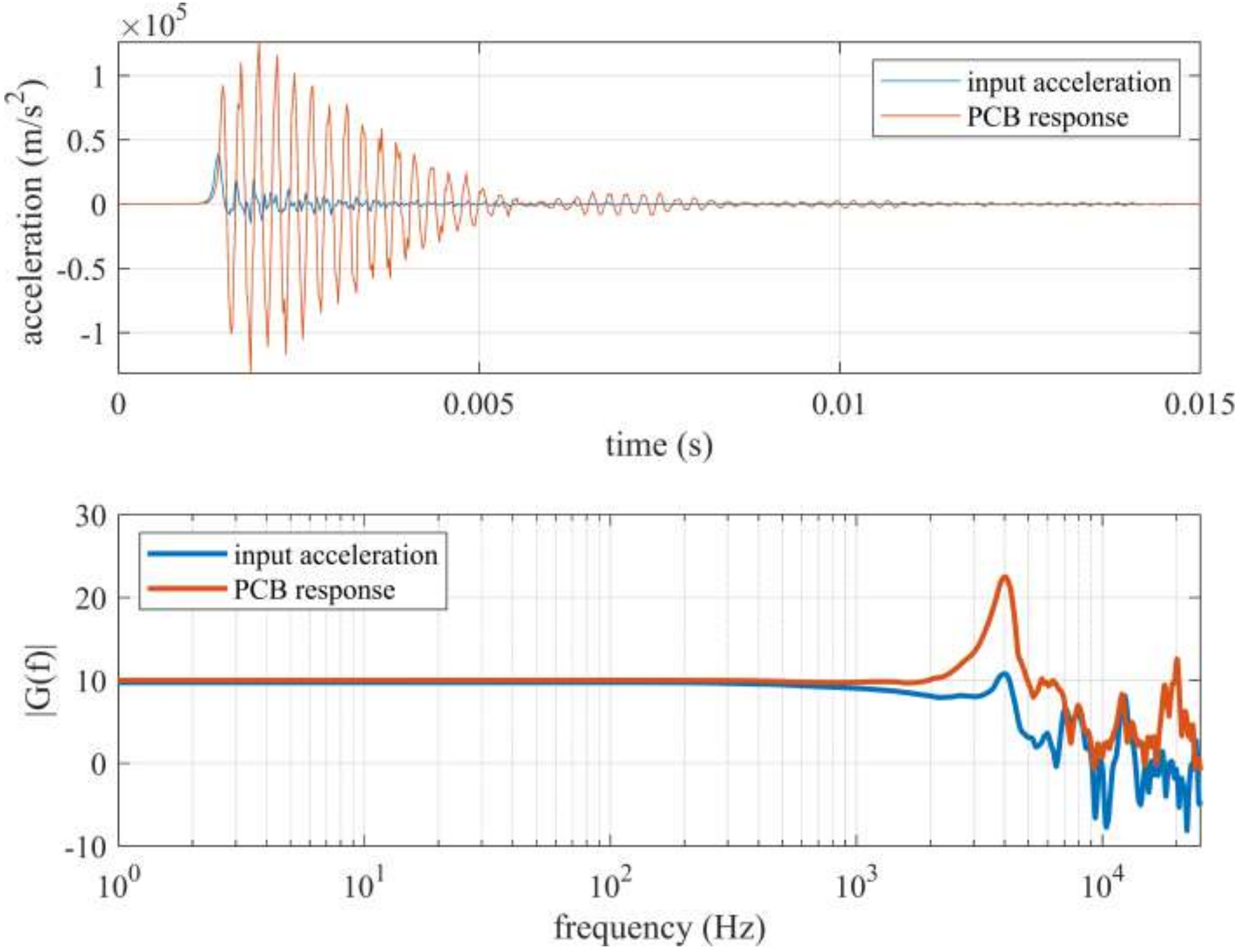






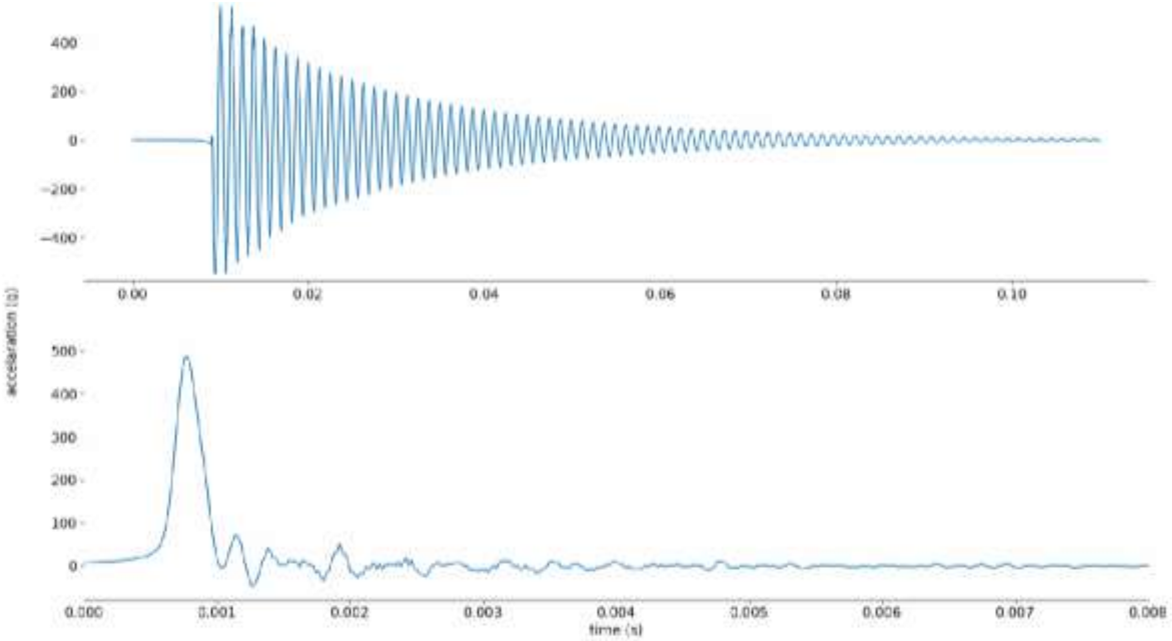
Experimental procedure





Experimental procedure

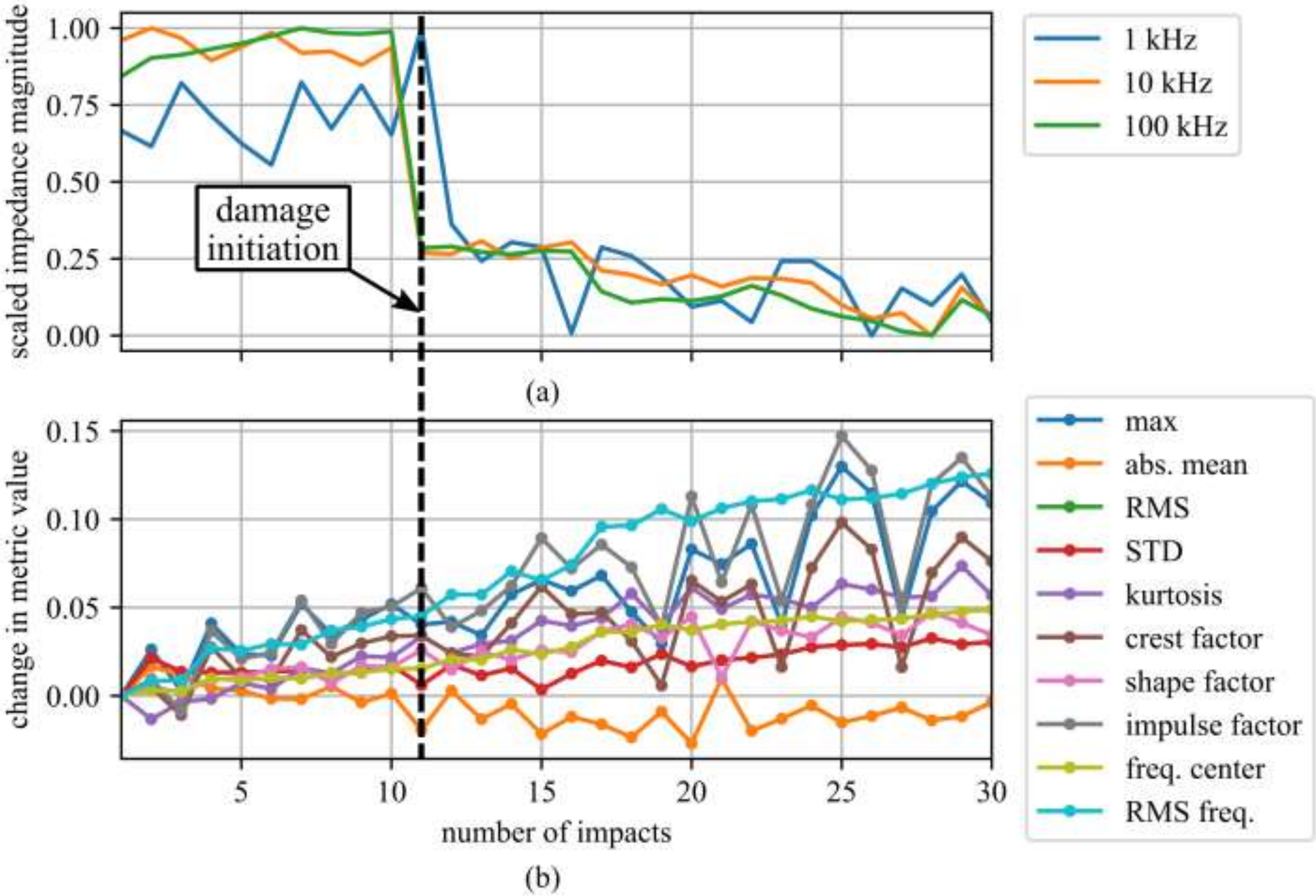
- Dataset encompasses 30 impacts
- Shock amplitude of over 10,000 g_n
- Average half-sine time of 32 μs
- PCB resonance 4000 Hz



Validation and feature extraction

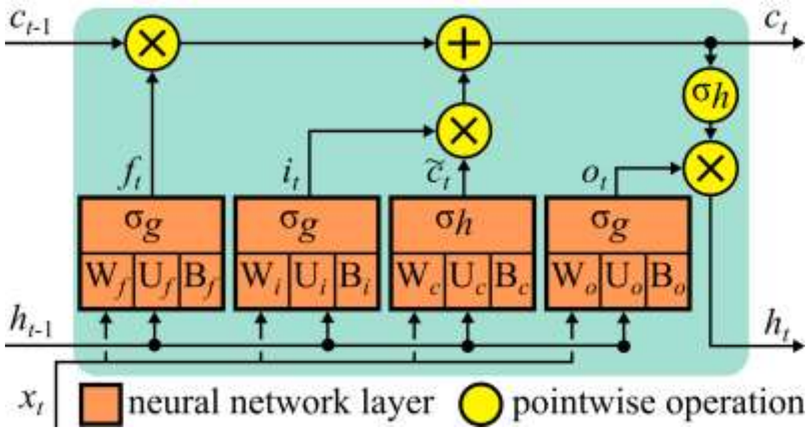
Table 1 Time-domain features

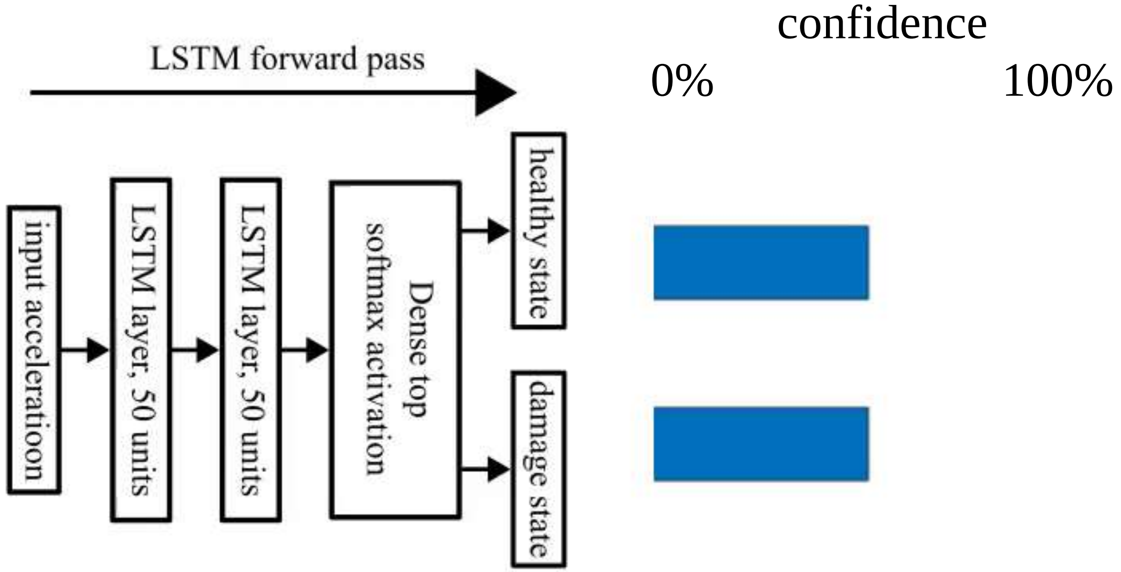
No.	Features	Description	Physical interpretation
T1	Maximum	$\text{Max}(X_i)$	Kinetic energy related
T2	Absolute Mean	$\text{Mean}(\lvert X_i \rvert)$	
T3	RMS	$\sqrt{\frac{\sum X_i^2}{N}}$	
T4	Skewness	$\frac{\sum (X_i - \bar{X})^3}{(N-1)s^3}$	Data statistics related
T5	Kurtosis	$\frac{\sum (X_i - \bar{X})^4}{(N-1)s^4}$	
T6	Crest Factor	$\frac{\text{Max}(X_i)}{X_{rms}}$	Sinusoidal wave shape related
T7	Shape Factor	$\frac{X_{rms}}{\text{Mean}(\lvert X_i \rvert)}$	
T8	Impulse Factor	$\frac{\text{Max}(X_i)}{\text{Mean}(\lvert X_i \rvert)}$	



Model development

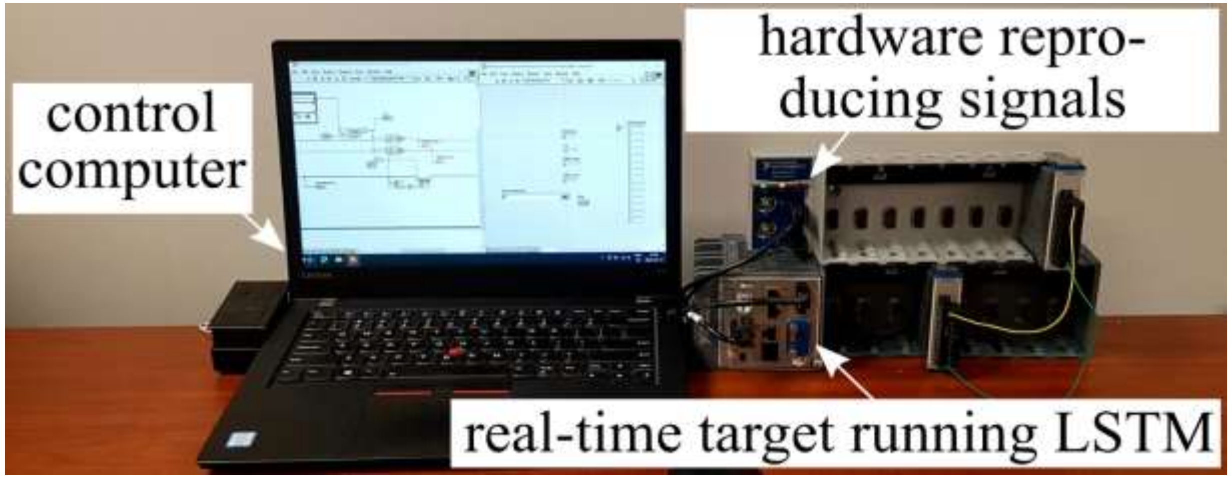
- Long short-term memory (LSTM) models are used for real-time state estimation.
- Models are initially trained offline on pre-recorded data.
- LSTM architecture is (50, 50 units) with a dense layer at the output with SoftMax activation

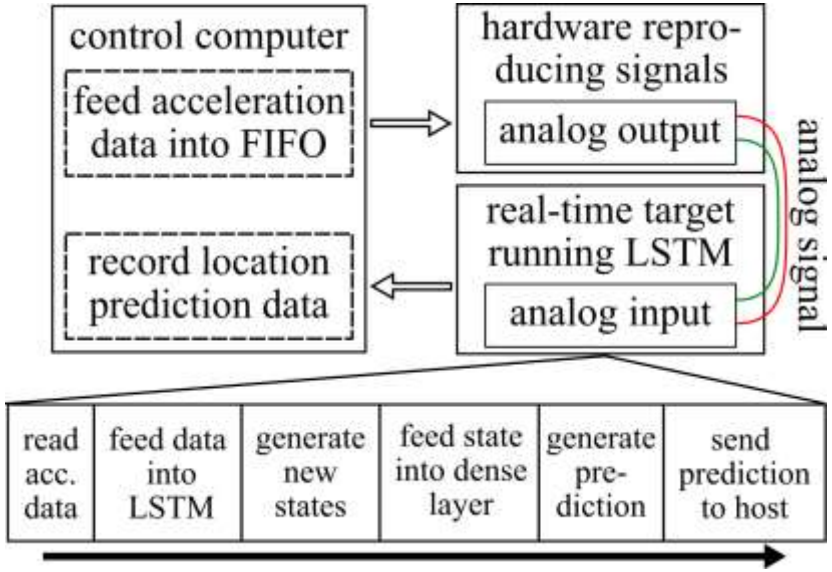




Model deployment

- A real-time system demonstrates an end-to-end prediction system.
- Signal reproduction is isolated from real-time system performing signal acquisition, state updating, and health estimation.
- Health estimates are communicated back to the host computer.





Virtex 7

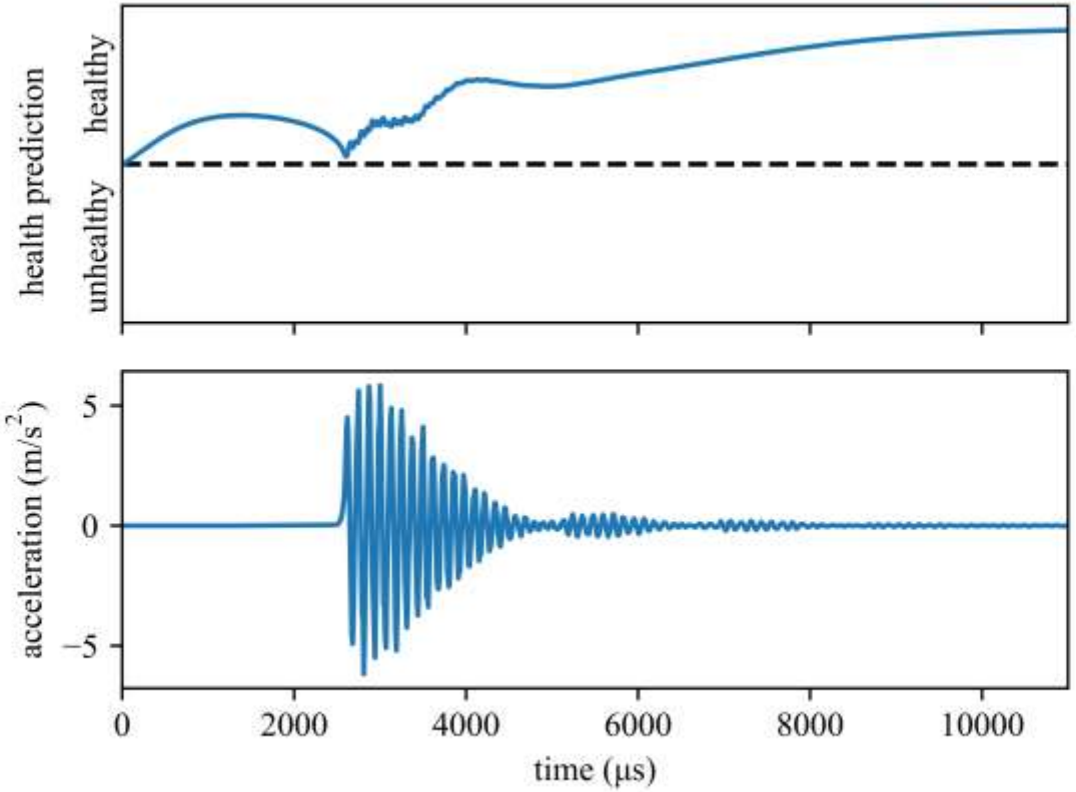
Alveo U55c

ZCU104

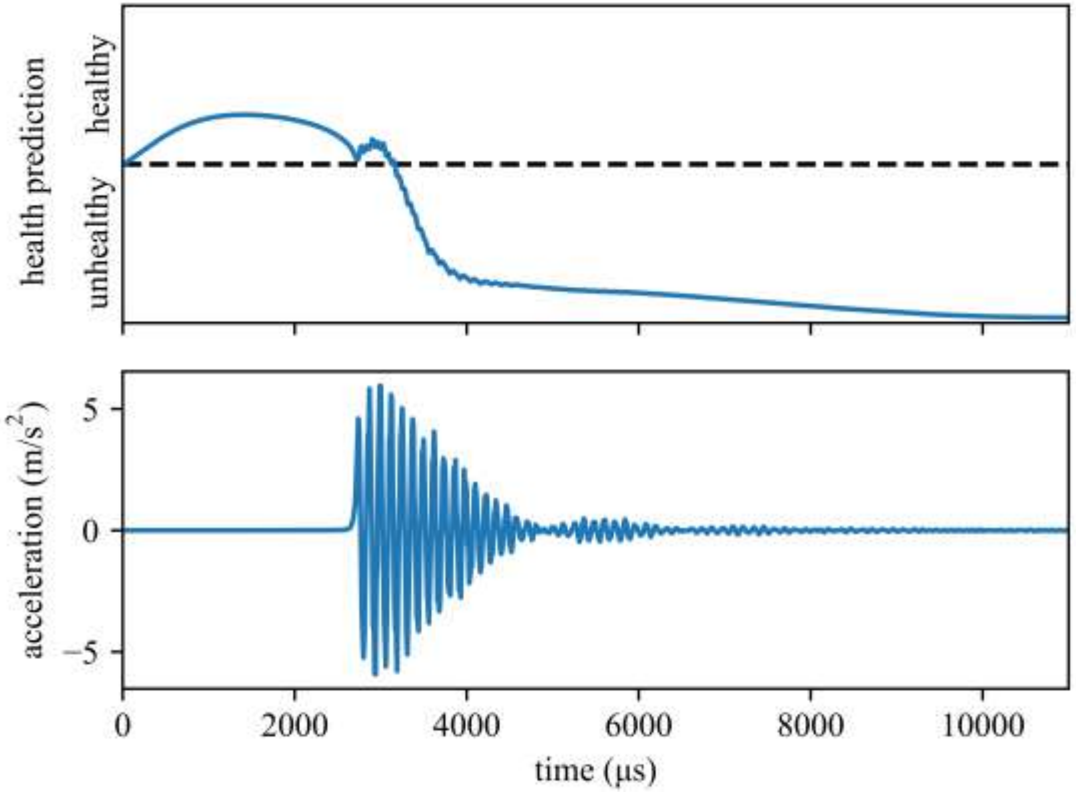
Model performance

prediction of survivability of PCB exposed to shock loads

healthy PCB



unhealthy PCB



Model performance

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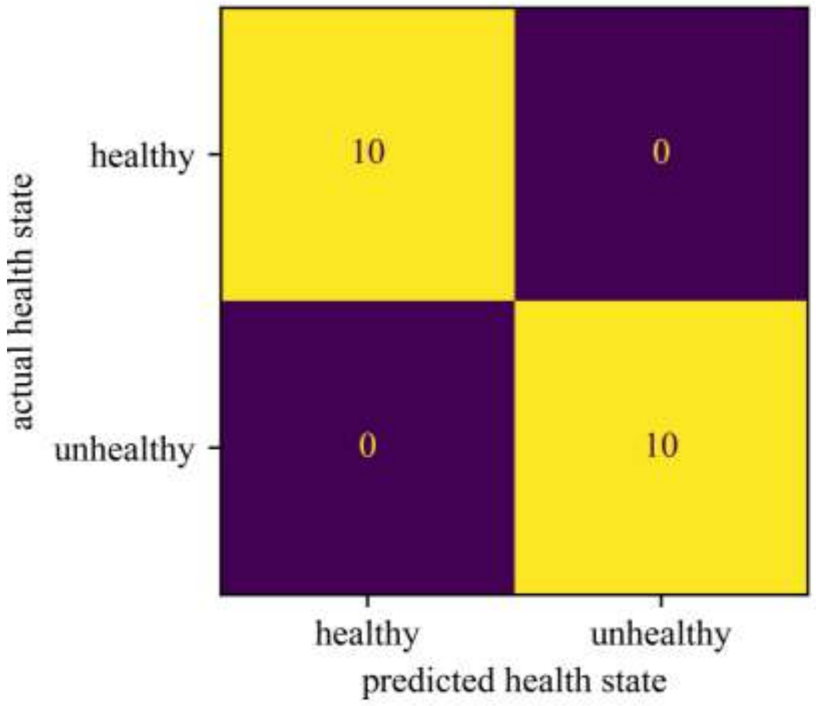
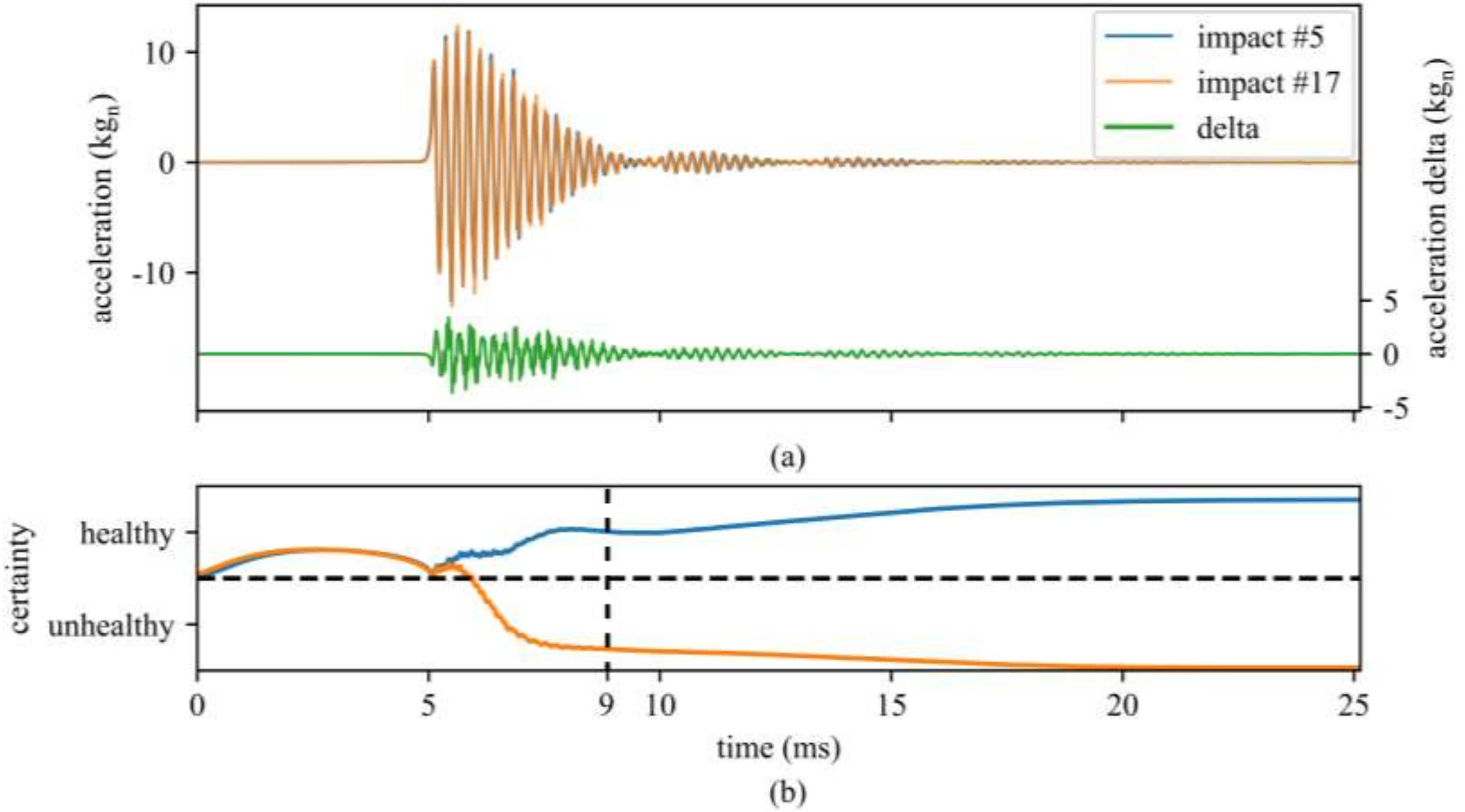
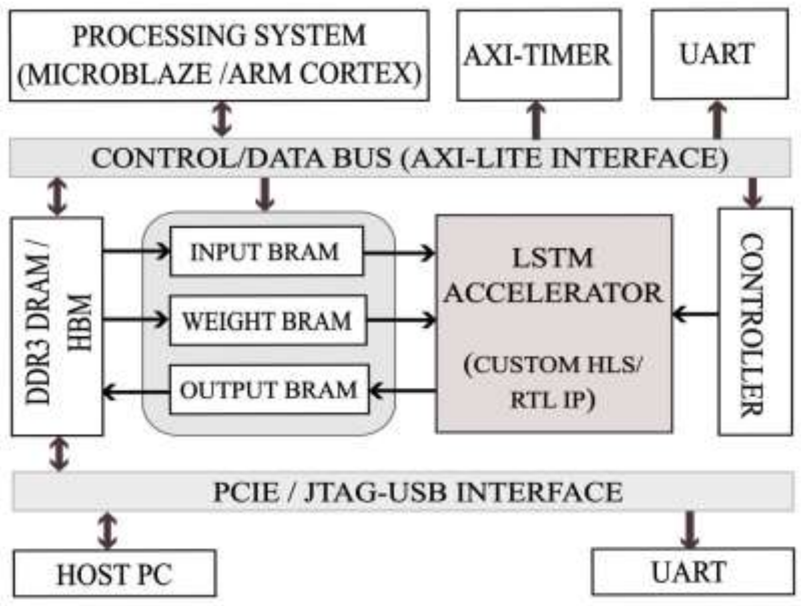




FPGA implementation

- Implemented in 16-bit fixed and 32-bit floating point.
- Developed an LSTM hardware accelerator using design of an LSTM accelerator framework using high-level synthesis (HLS)
- Goal: to meets the real-time requirements set by high-rate applications.
- Note that outermost loop pipelining generates a more efficient hardware design than outermost loop unrolling of the algorithm.



ZCU104
(Zynq UltraScale+XCZU7EV-2FFVC1156 MPSoC)

VC707
(Virtex-7 XC7VX485TFFG1761-2)

U55C
(UltraScale+XCU55C-FSVH2892-2L-E)

Timing and resource utilization

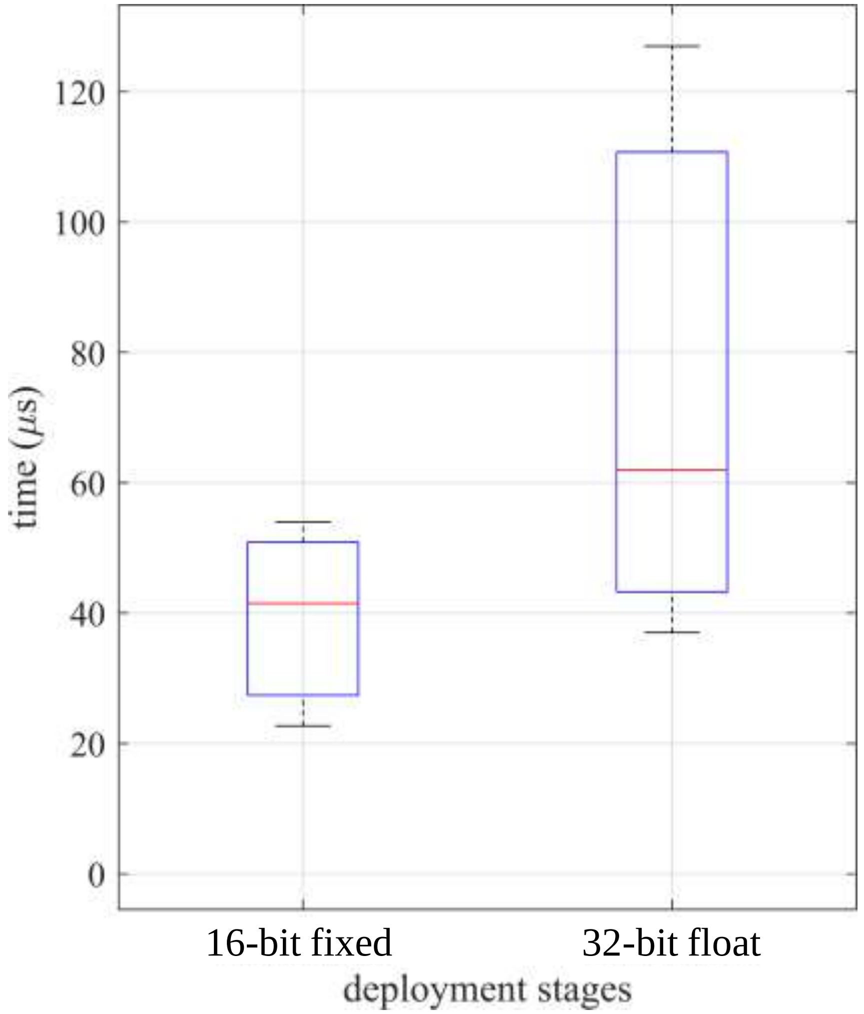
FPGA	Data Format	DSPs	BRAMs_18k	LUTs	FFs	Frequency (MHz)	Latency (µs)
Alveo U55c	Fixed 16 bit	470	416	75924	112625	283	22.7
ZCU104		454	242	32354	57956	280	41.5
Virtex 7		489	254	92534	129839	220	54

FPGA	Data Format	DSPs	BRAMs_18k	LUTs	FFs	Frequency (MHz)	Latency (µs)
Alveo U55c	Float 32 bit	1177	653	142344	242989	300	37
ZCU104		769	479	136242	263580	270	62
Virtex 7		769	487	192925	316056	150	127


Virtex 7

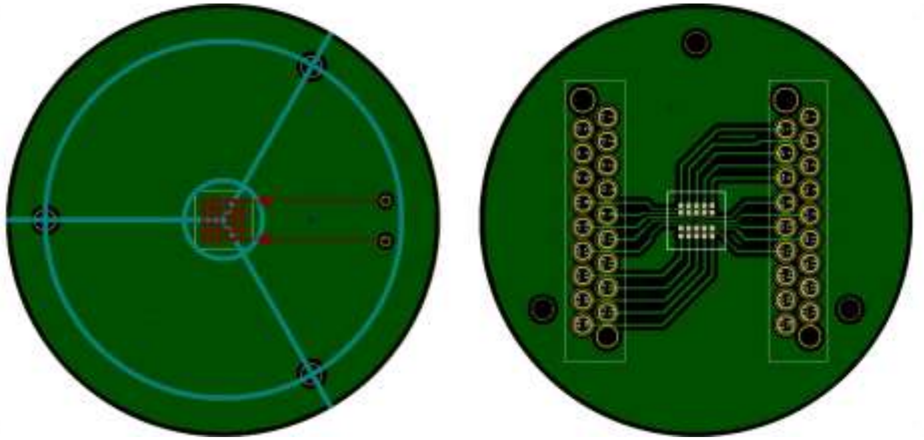

Alveo U55c

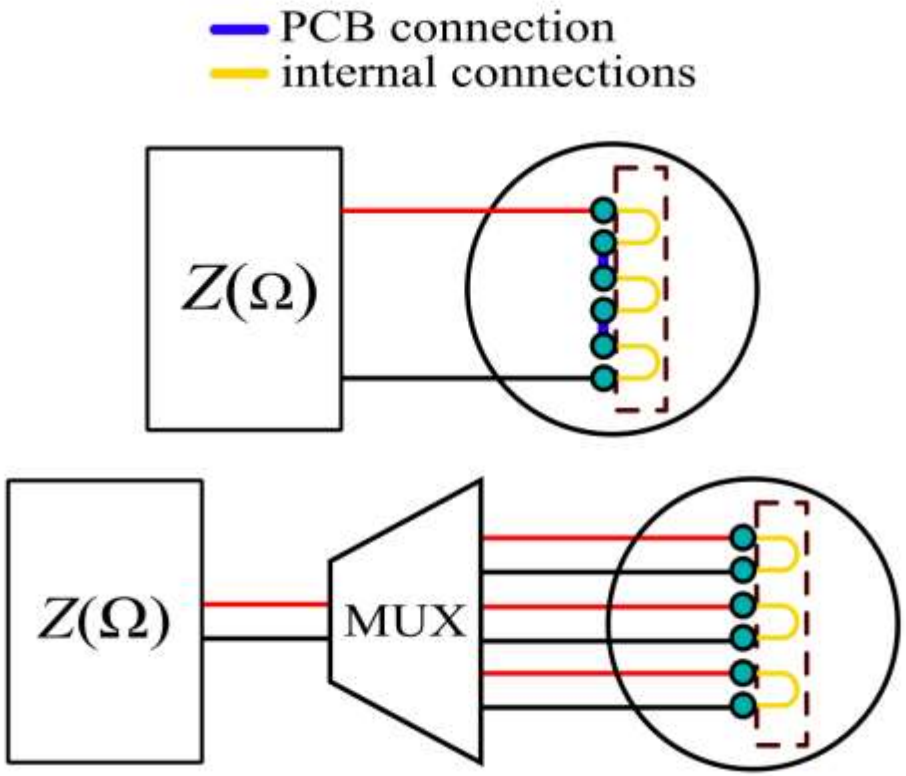

ZCU104



Future work

- Multi-connection impedance measurement
- Reduce latency and maximize model performance





Dataset Layout

https://github.com/High-Rate-SHM-Working-Group/Dataset-5-Extended-Impact-Testing/tree/main/data/dataset-2

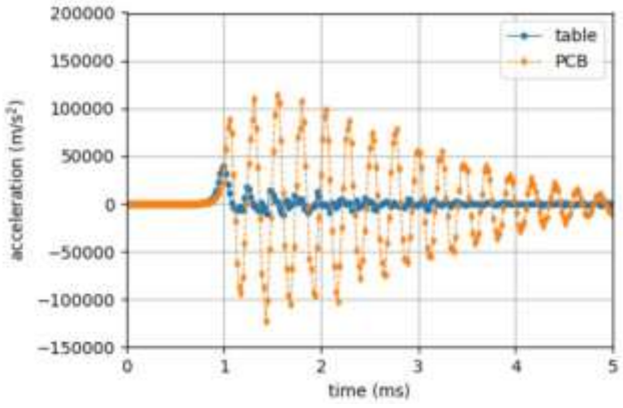
Dataset-5-Extended-Impact-Testing / data / dataset-2 /

Name	Last commit message
..	
data-1	Delete README.md
media/initial_microscope_images	added image annotation file
README.md	Update README.md

README.md

Dataset 2

Dataset 2 consists of 32 tests performed May 5 2023. Tests were performed consecutively on the same PCB. Following each impact test, impedance was measured at five LCR excitation frequencies. The folder also contains a python file with a demonstration for extracting data from the .lvm files and plotting, and figures plotting the acceleration and measured impedance.



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Thank you
Questions?

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References:

[1] Hong, J., Laflamme, S., Dodson, J., and Joyce, B., 2018. “Introduction to state estimation of high-rate system dynamics”. Sensors, 18(2), Jan., p. 217. [2] Dodson, J., Downey, A., Laflamme, S., Todd, M. D., Moura, A. G., Wang, Y., Mao, Z., Avitabile, P., and Blasch, E., 2021. High-Rate Structural Health Monitoring and Prognostics: An Overview. Springer International Publishing, Oct., pp. 213–217. [3] Lall, P., Panchagade, D., Iyengar, D., Shantaram, S., Suhling, J., and Schrier, H., 2007. “High speed digital image correlation for transient-shock reliability of electronics”. In 2007 Proceedings 57th Electronic Components and Technology Conference, IEEE, pp. 924–939. [4] Lall, P., Pandurangan, A. R. R., Dornala, K., Suhling, J., Deep, J., and Lowe, R., 2019. “Effect of shock pulse variation on surface mount electronics under high-g shock”. In 2019 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), IEEE, pp. 586–594. [5] Amy, R. A., Aglietti, G. S., and Richardson, G., 2009. “Reliability analysis of electronic equipment subjected to shock and vibration–a review”. Shock and Vibration, 16(1), pp. 45–59.

[6] Steinberg, D. S., 2000. “Vibration analysis for electronic equipment”.

[7] Liu, K.-T., Lu, C.-L., Tai, N., and Yeh, M. K., 2020. “Stress analysis of printed circuit board with different thickness and composite materials under shock loading”. Computer Modeling in Engineering & Sciences. [8] Esser, B., and Huston, D., 2004. “Active mass damping of electronic circuit boards”. Journal of Sound and Vibration, 277(1–2), Oct., pp. 419–428. [9] Chomette, B., Chesné, S., Rémond, D., and Gaudiller, L., 2010. “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), Feb., pp. 352–364. [10] Downey, A., Dodson, J., Vereen, A., Satme, J., and Nelson, C., 2022. Dataset-5-extended-impacttesting. https://github.com/High-Rate-SHM-WorkingGroup/Dataset-5-Extended-Impact-Testing. [11] Satme, J., and Coble, D., 2024. Paper-online-healthmonitoring-of-electronic-components-subjected-torepeated-high-energy-shock. https://github.com/ARTSLaboratory/Paper-Online-Health-Monitoring-ofElectronic-Components-Subjected-to-Repeated-Highenergy-Shock. [12] Thompson, Z., Vereen, A., Downey, A., Bakos, J. D., Dodson, J., and Moura, A. G., 2023. Online Backpropagation of Recurrent Neural Network for Forecasting Nonstationary Structural Responses. Springer Nature Switzerland, pp. 133–137.