# Advances in Machine Learning at the Edge for Enhanced Structural Health Monitoring and Control in SWaP-Constrained Environments

Adaptive Real-Time Systems Laboratory (ARTS-Lab)

An Interdisciplinary Controls Lab at USC

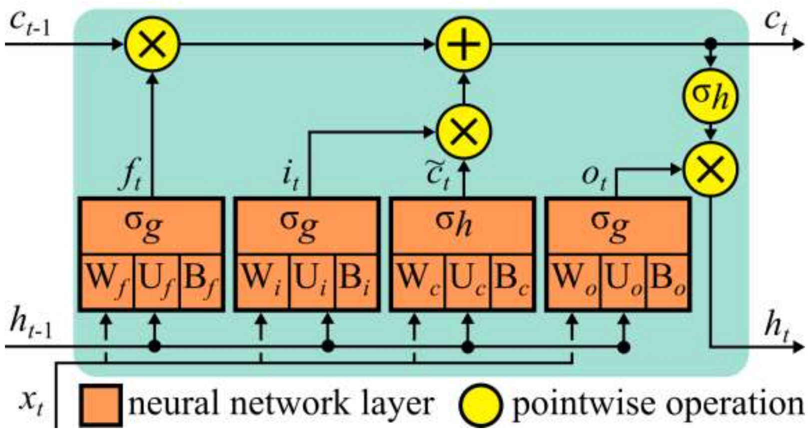

**Austin R.J. Downey**
Associate Professor
Mechanical Engineering
Civil and Environmental Engineering


UNIVERSITY OF South Carolina

Molinaroli College of Engineering and Computing

# Introduction

- **Part 1:** Overview of the ARTS-Lab
- **Part 2:** High-rate ML at the Edge
- **Part 3:** Signal Processing for UAV-deployed Sensors




# About the ARTS-Lab

- **An Interdisciplinary Controls Lab** at the University of South Carolina.
- **Slogan:** “Hardware Keeps the Engineer Honest”—we focus on real-world validation of our research.
- **Aspirations:** Develop cutting-edge innovations and enable unparalleled student success.

University of South Carolina Campus

# Mentorship & Student Growth

- **8 current Ph.D. students:** 2 graduated, 1 in academia.
- **7 current M.S. students:** 7 graduated.
- **23 current undergraduates:** 71 graduated, 2 NSF GFRP, 1 DoD SMART.
- **A growing alumni network:** past students have gone on to Government Labs and top graduate programs.
- **Undergraduates take part in real research:** leading conference and journal publications, and hardware development.
- **Commitment to Open Source:** We believe in democratizing knowledge through open-source software and hardware.

# How We See Ourselves

We use

foundational science

Day School

to develop essential tools

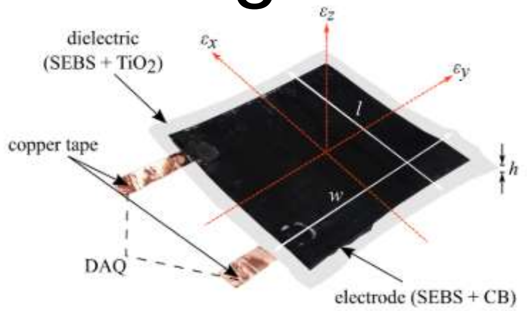
Dan Thompson

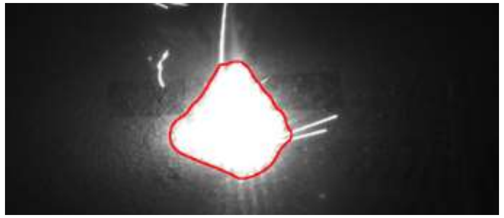
to solve real-world problems

public domain

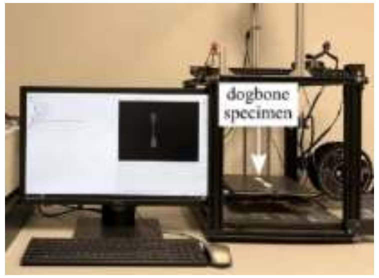
**We are Engineers (mostly)**

# Sensing

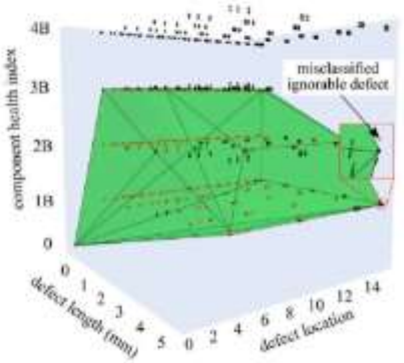


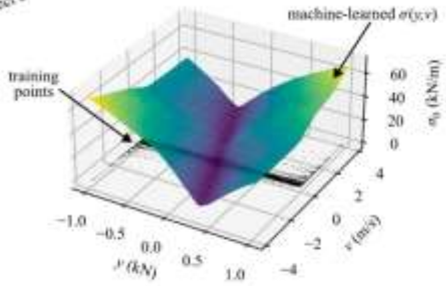



# Data Assimilation

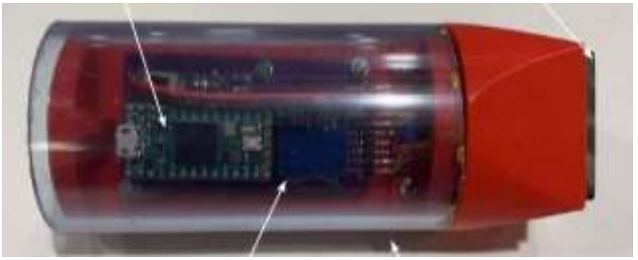



# AI/ML

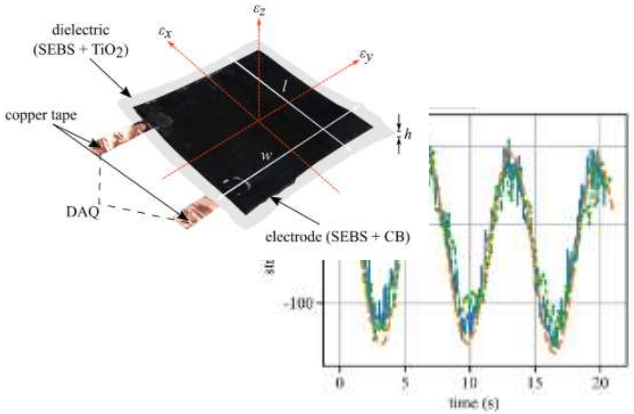


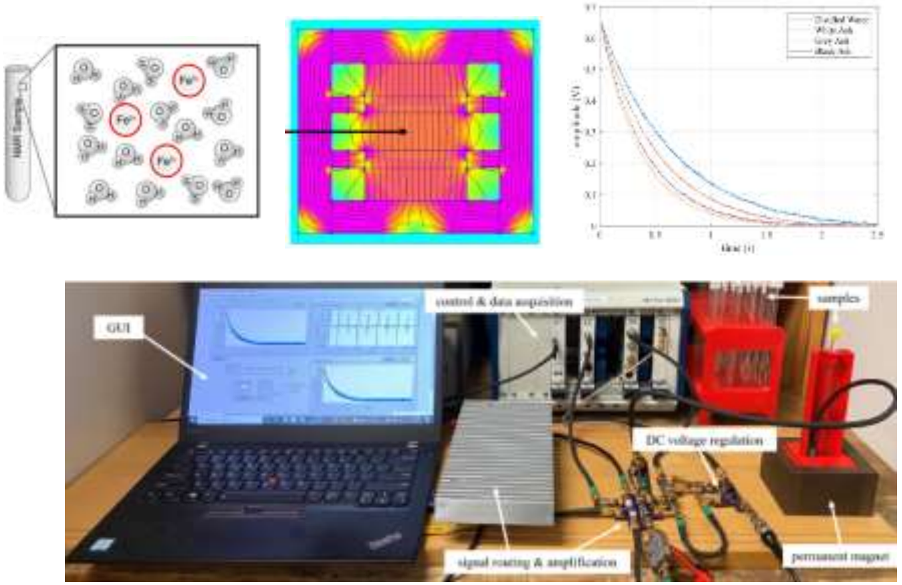

# Embedded Systems

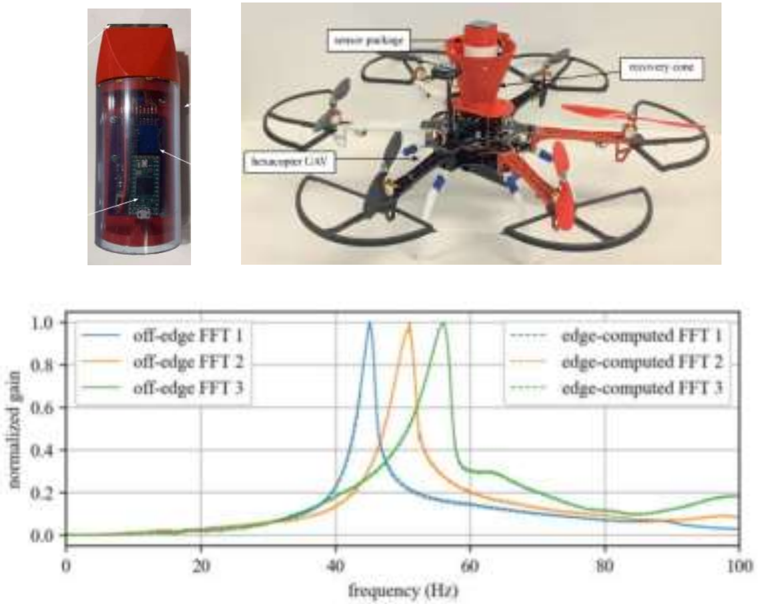
# Sensing



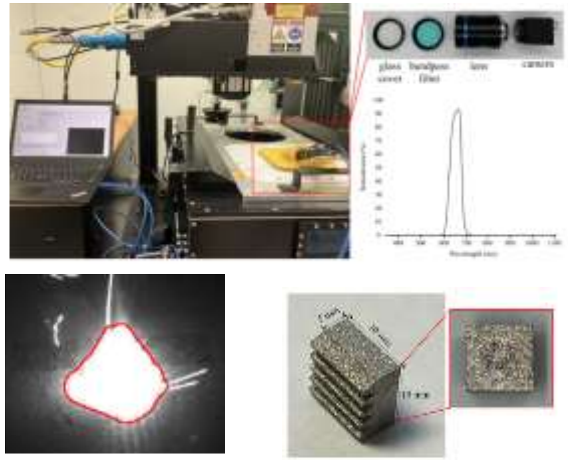

Flexible Electronics



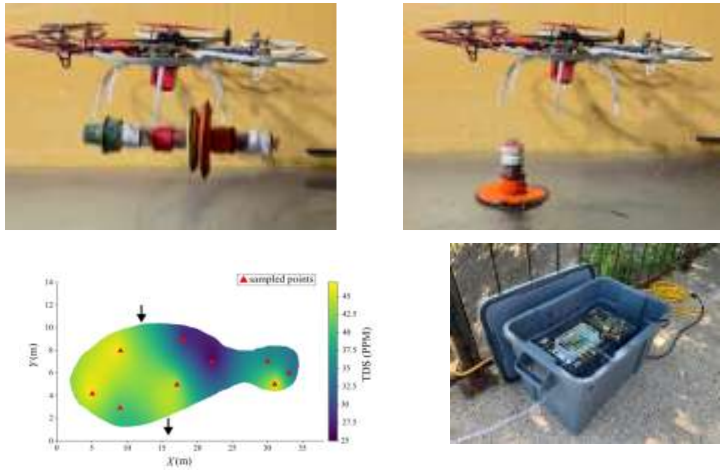

Nuclear Magnetic Resonance



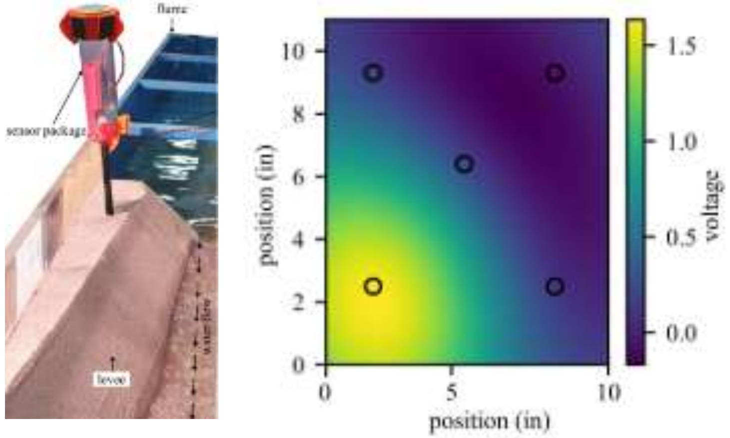

Vibration Sensors



In Situ Monitoring of AM

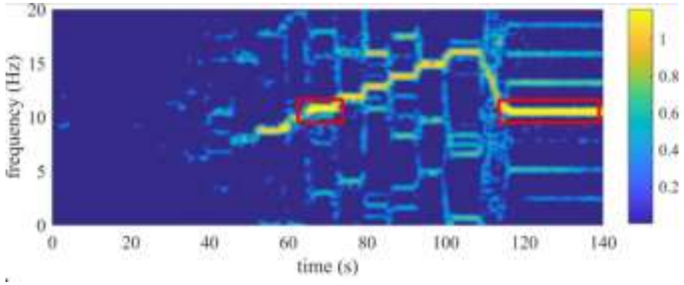



Water Quality Sensors

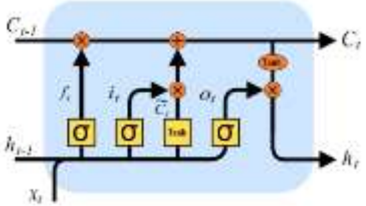



Geo Technical Sensors

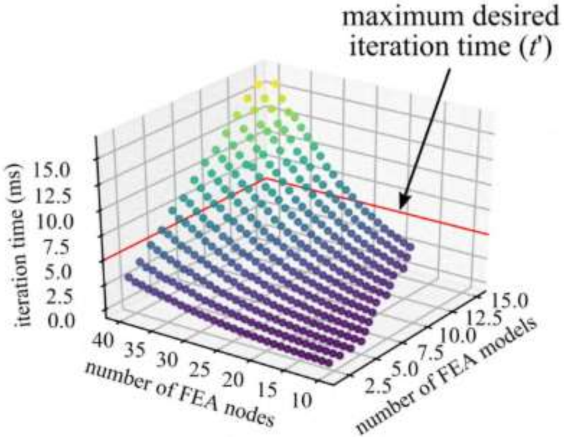
# Data Assimilation



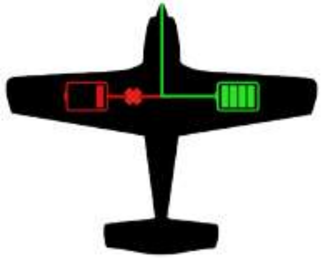

Civil Structures

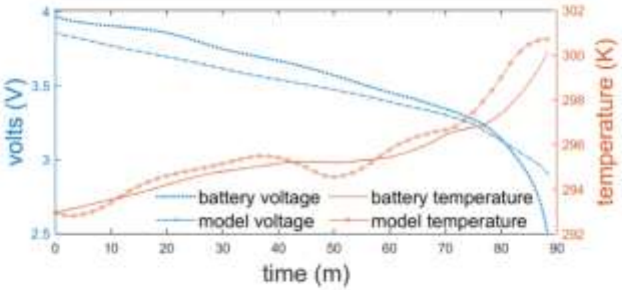


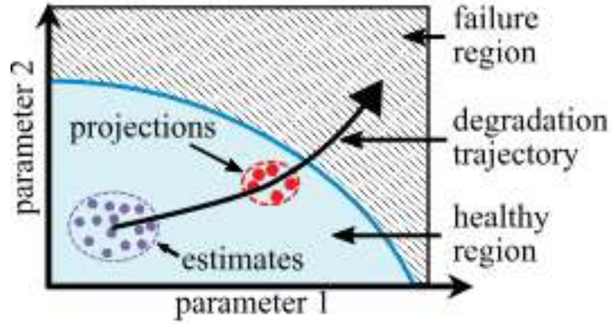

$$\frac{-1}{\alpha} = \sum_{r=1}^{m} \frac{v_r^2}{\omega_r^2 - \Omega_r^2}$$




High-Rate Systems

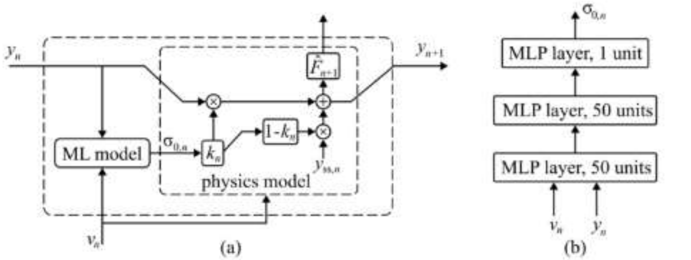


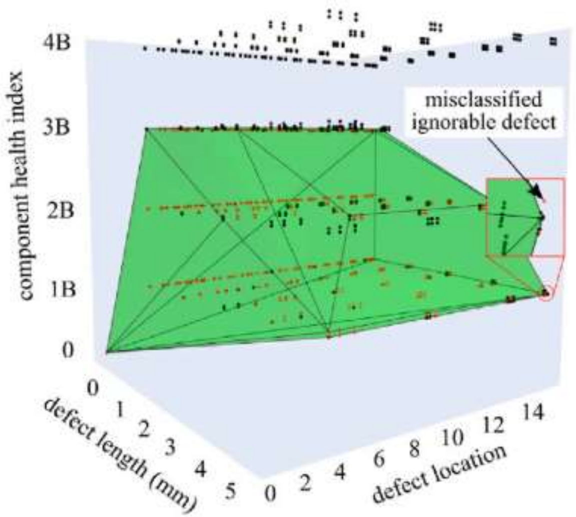


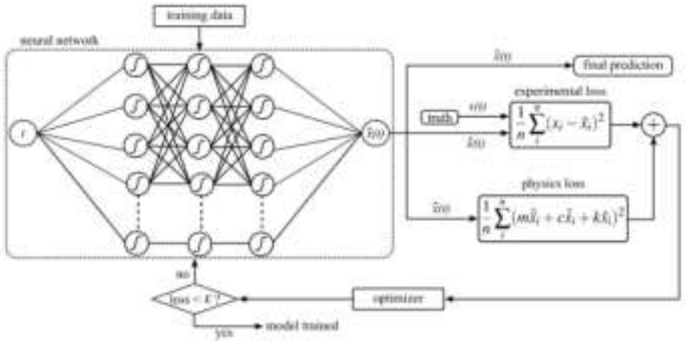

Battery Systems

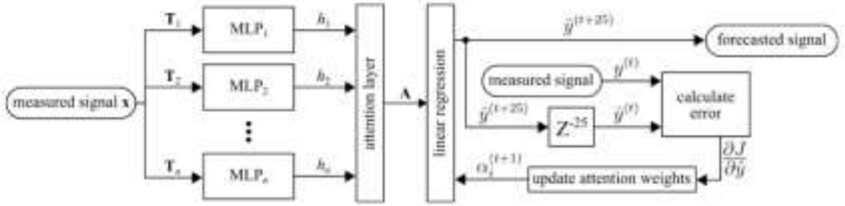
# AI/ML

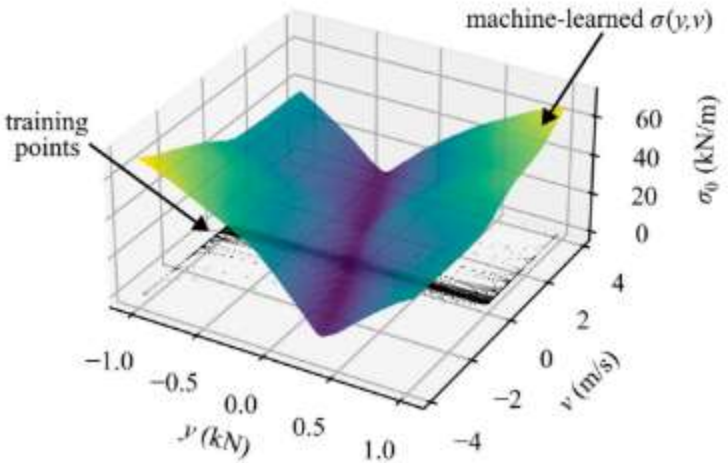


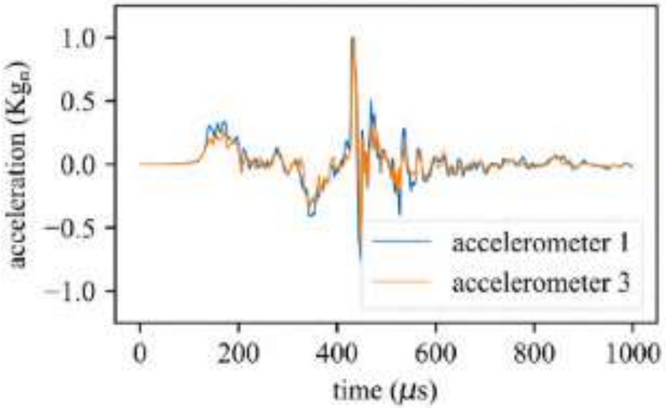



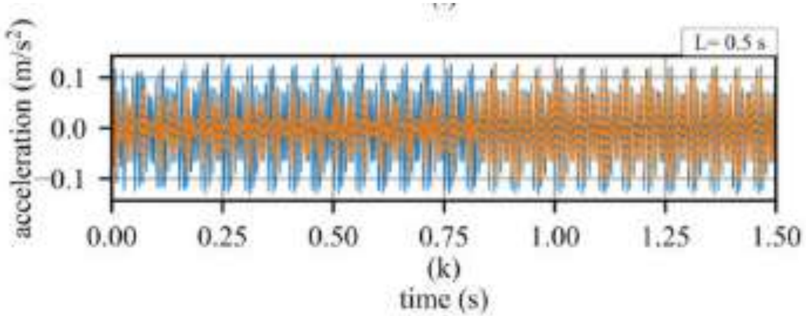

Decision-making





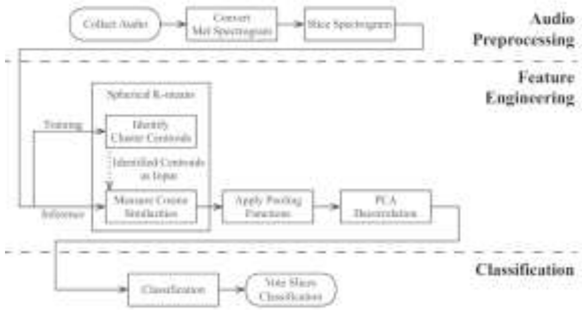




Explainability

Generative

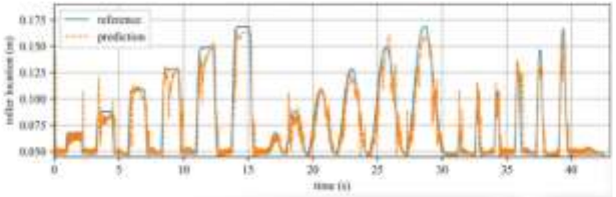
Forecasting

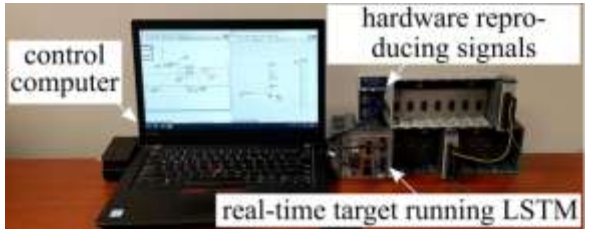
# Embedded Systems

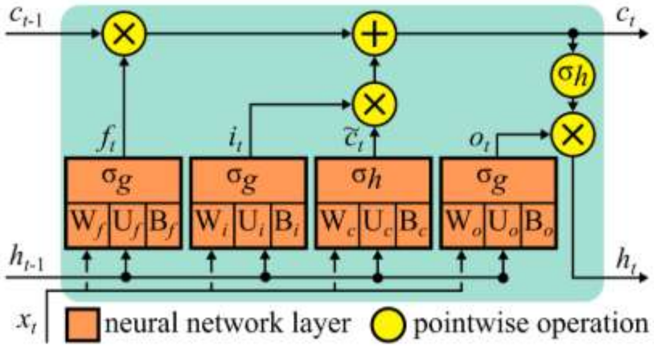




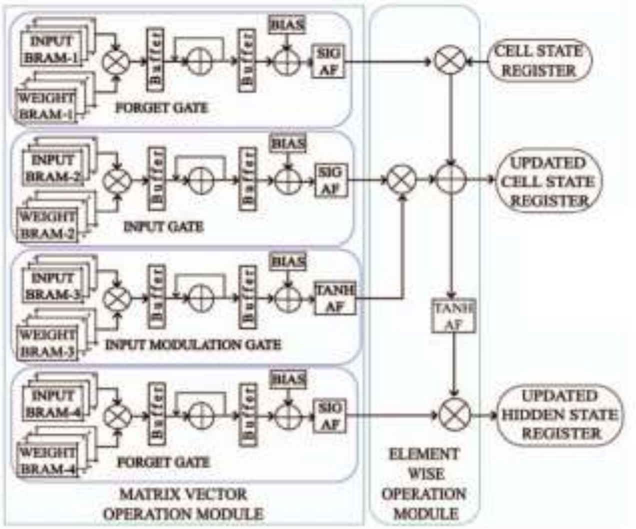
Microcontroller/
microprocessor

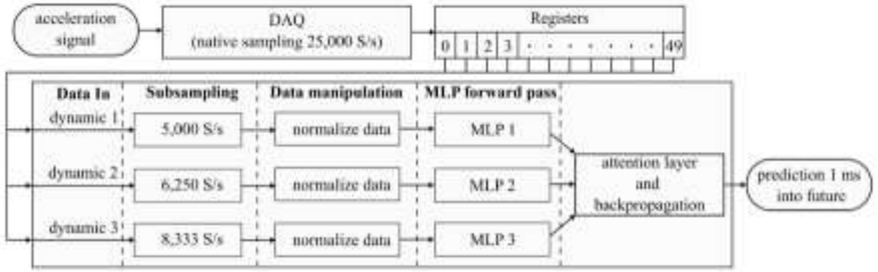



Real-Time OS




FPGA

# Supporting Agencies, Companies, and Partners

NSF

AFRL
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

Office of Naval Research
ONR
Science & Technology

DEPARTMENT OF THE ARMY
UNITED STATES OF AMERICA
1775

NAVSEA
WARFARE CENTERS
Carderock

dhec

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

SCRA
South Carolina Research Authority

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

NASA SC Space Grant Consortium

NASA

HALLIBURTON

FULBRIGHT
Association

SOUTH CAROLINA GOVERNOR'S SCHOOL FOR
SCIENCE + MATHEMATICS

# Out Academic Partners

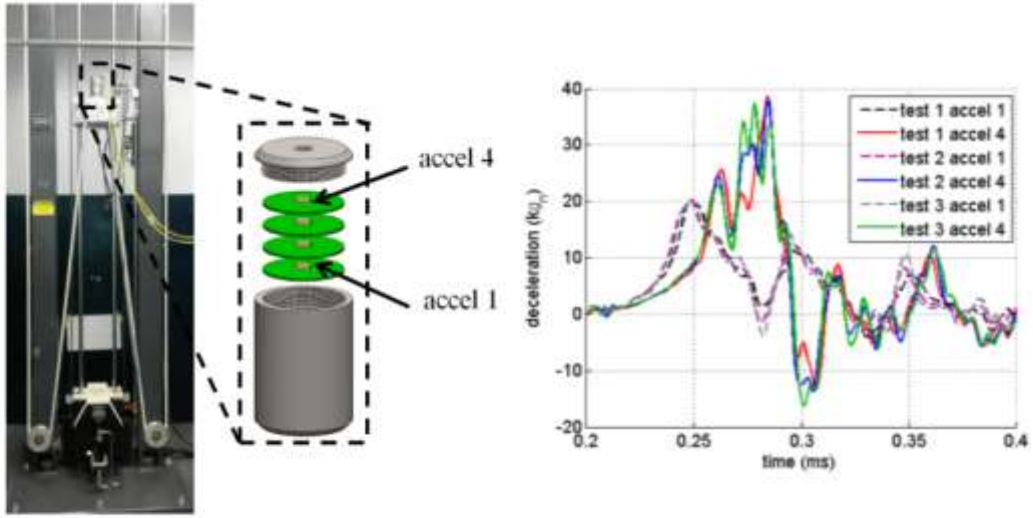
# Part 2: High-rate ML at the Edge

# Description of High-rate Dynamics

High-rate (<100ms)

High-amplitude (acceleration > 100 *g*)

The deceleration event in drop tower tests typically lasts for 0.5ms




- Large uncertainties in the external loads.
- High levels of nonstationarity and heavy disturbance.
- Generations of unmodeled dynamics from changes in mechanical configuration.



Hong, J. et al,. *Introduction to state estimation of high-rate system dynamics*. Sensors, 18(2):217, Jan 2018

# High-Rate Systems

Hypersonic vehicles

Ballistic packages

Debris approaching space shuttle

Lightning strikes on aircraft

Civil Structures

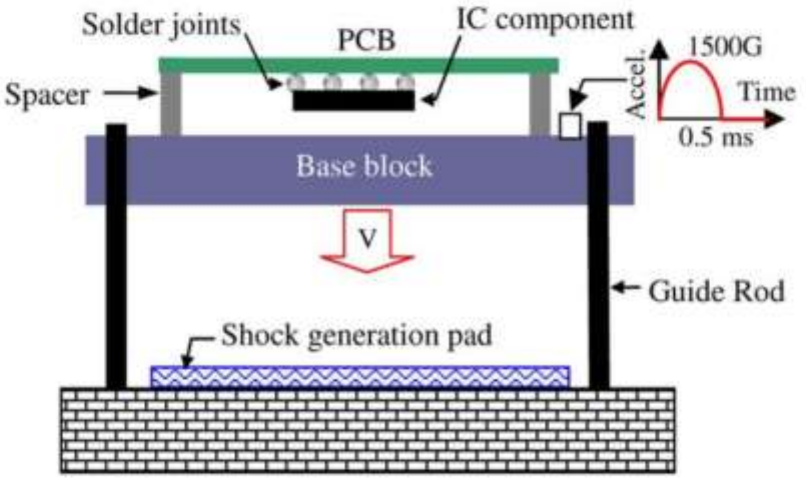
Fighter jets

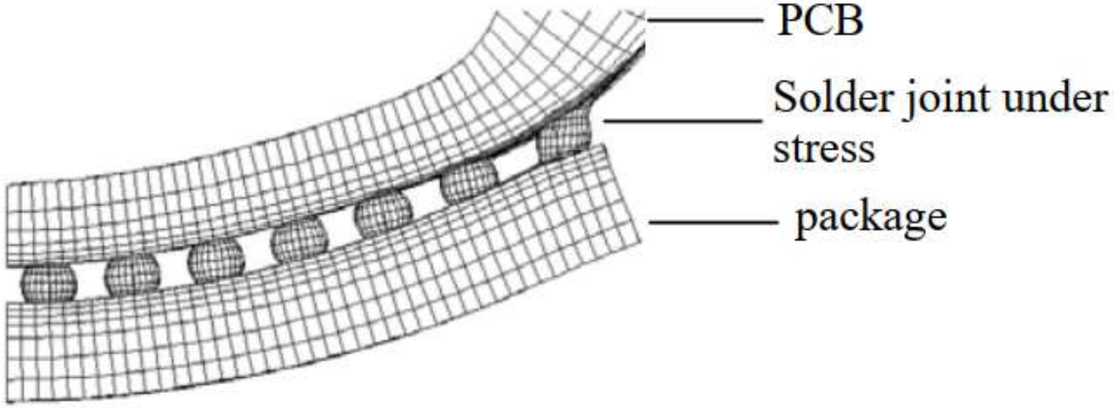
# Active High-Rate Systems (Airbags)

# Active High-Rate Systems (Electronics)

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.

# Data Driven or Physics Based State Estimation

?

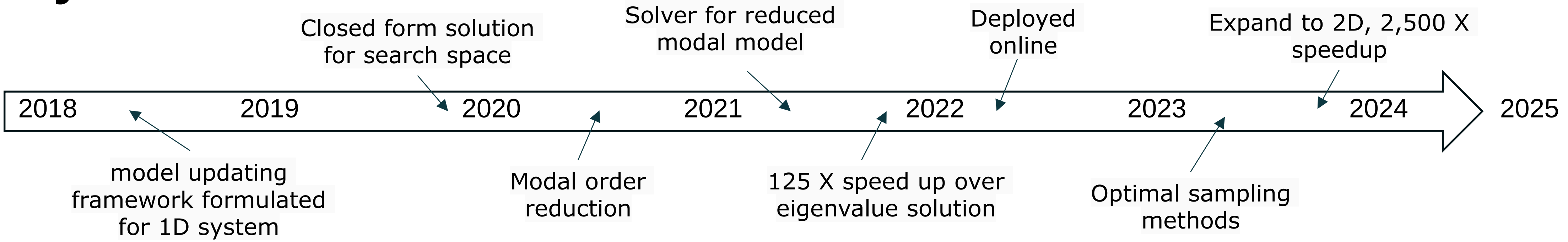
# Data Driven or Physics Based State Estimation

- **Data-driven**:
  - Potential to be faster
  - Easier to implement
  - Students excited to work on it
  - AI/ML is moving quickly
- **Physics-based**:
  - Potential for prognostics
  - Potential for real-time control
  - Better suited for decision-making
  - Better suited for un-foreseen dynamics

It was hard to decide, so we did both

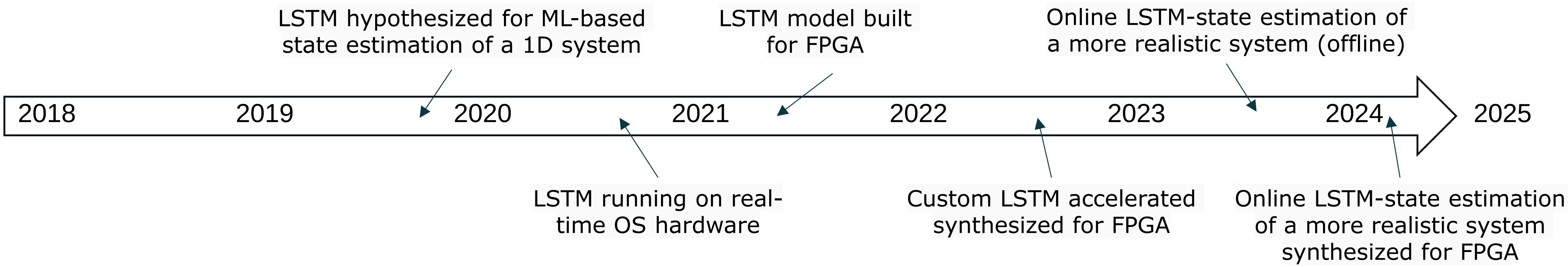
# Timeline of Efforts on State Estimation

## Physics-based - YIP




YIP

## Data-driven




CRII/
CAREER

# Data Driven Model Updating
# (Theory and Proof of Concept)

Data Driven Model Updating (Theory and Proof of Concept)

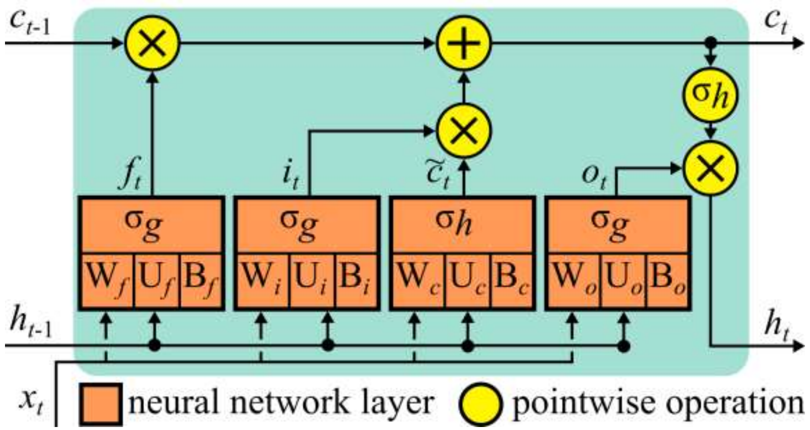
Electronic Components Under Shock (Application)

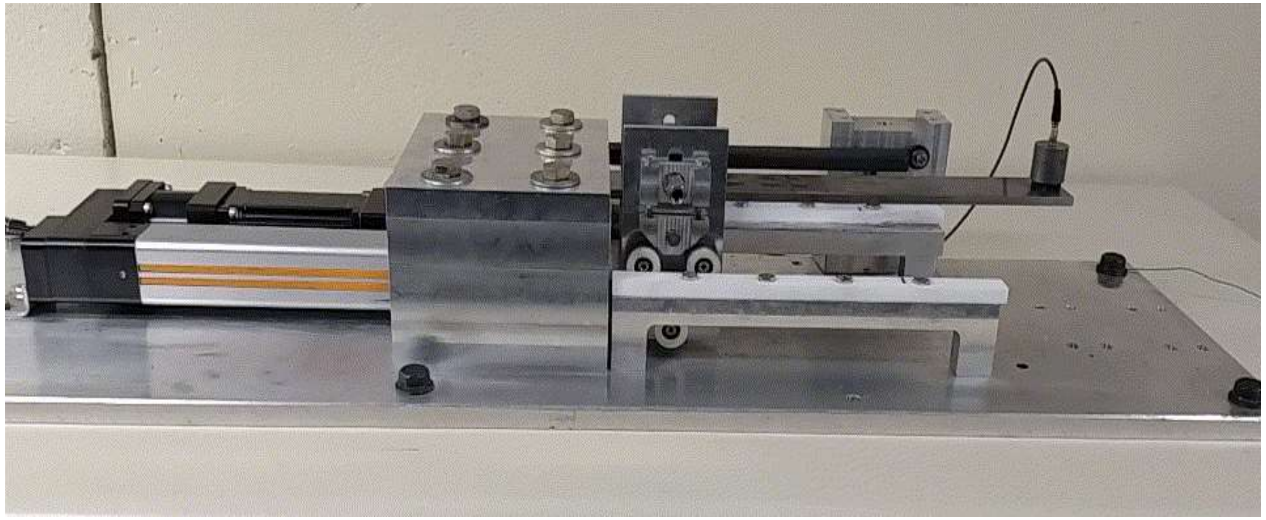
FPGA Implementation (Timing Consideration)

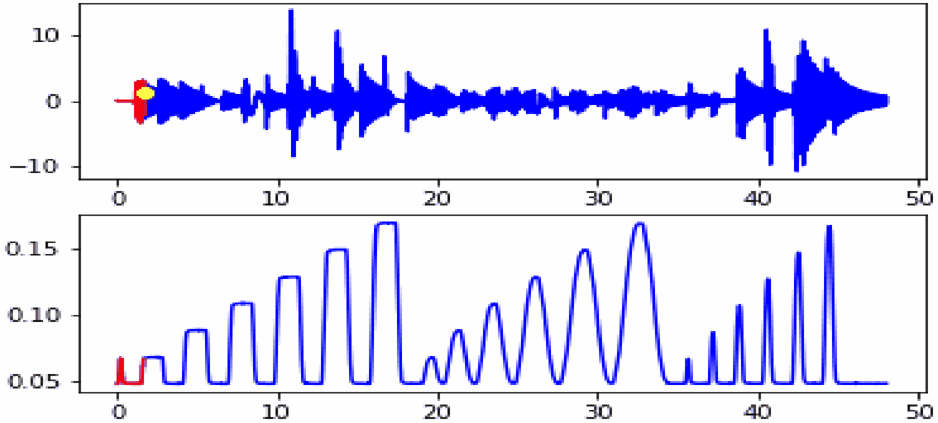
# LSTM-based Real-time State Estimation

In this work:

- Long short-term memory (LSTM) models are used for real-time state estimation.
- Experimentally validated on NI-Linux Real-Time.



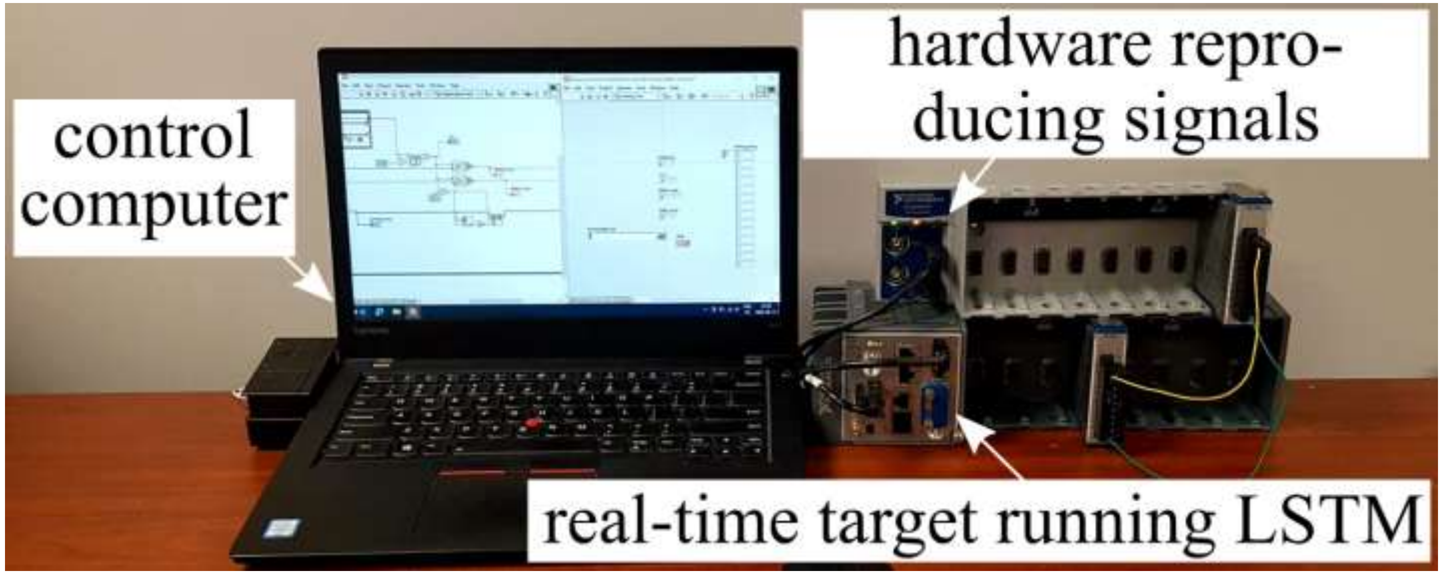



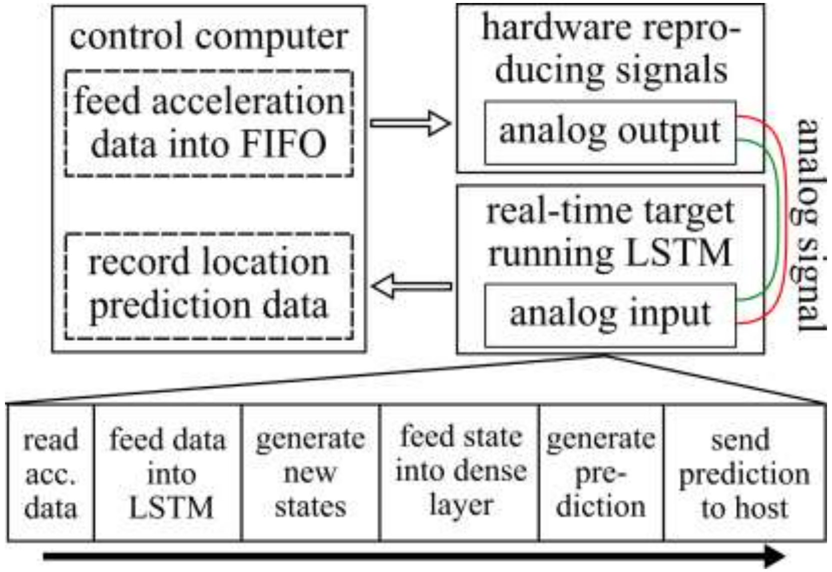


# Real-time Validation on Embedded Systems

Real-time validation performed on an embedded system running:

- **Hardware reproducing Signals** reproduces the DROPBEAR.
- **Real-time Target** digitizes the analog voltage and feeds the input LSTM.
- Data is sampled at 400 S/s, therefore, a prediction is made every 2.5 ms.



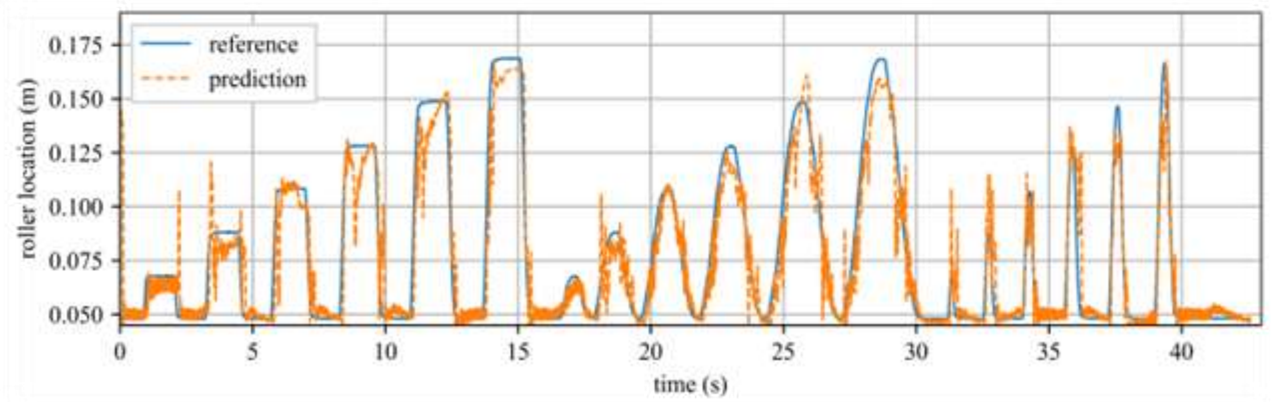
# Real-time LSTM Modeling Results

LSTM model performance results:

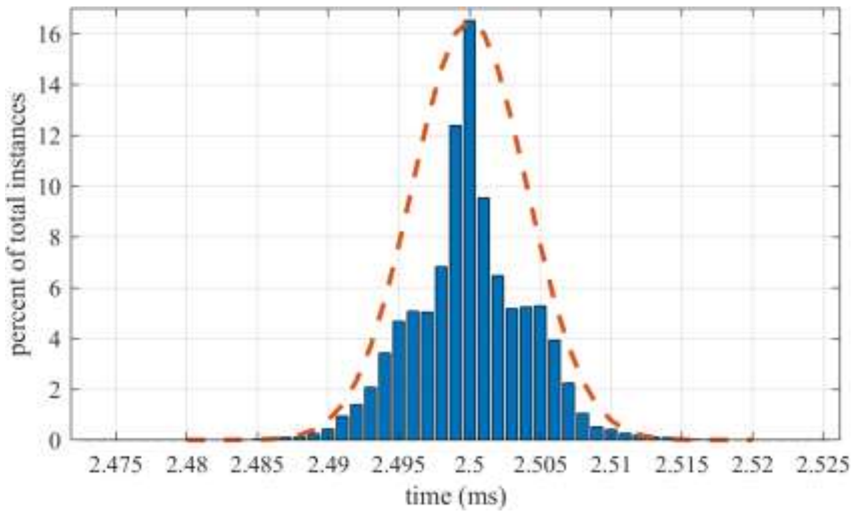
- $SNR_{dB}$ of 43.2 dB.
- RMSE of 12.8 mm.
- LSTM traces reference pin location closely.

Timing accuracy results:

- Execution-time jitter in observed (expected).
- Timing follows a normal distribution.




**Algorithm Timing**




| | |
|---|---|
| Mean | 2.5 ms |
| Standard deviation | 0.004 ms |
| Max overshoot | 0.019 ms |

# Electronic Components Under Shock (Application)

Data Driven Model Updating (Theory and Proof of Concept)

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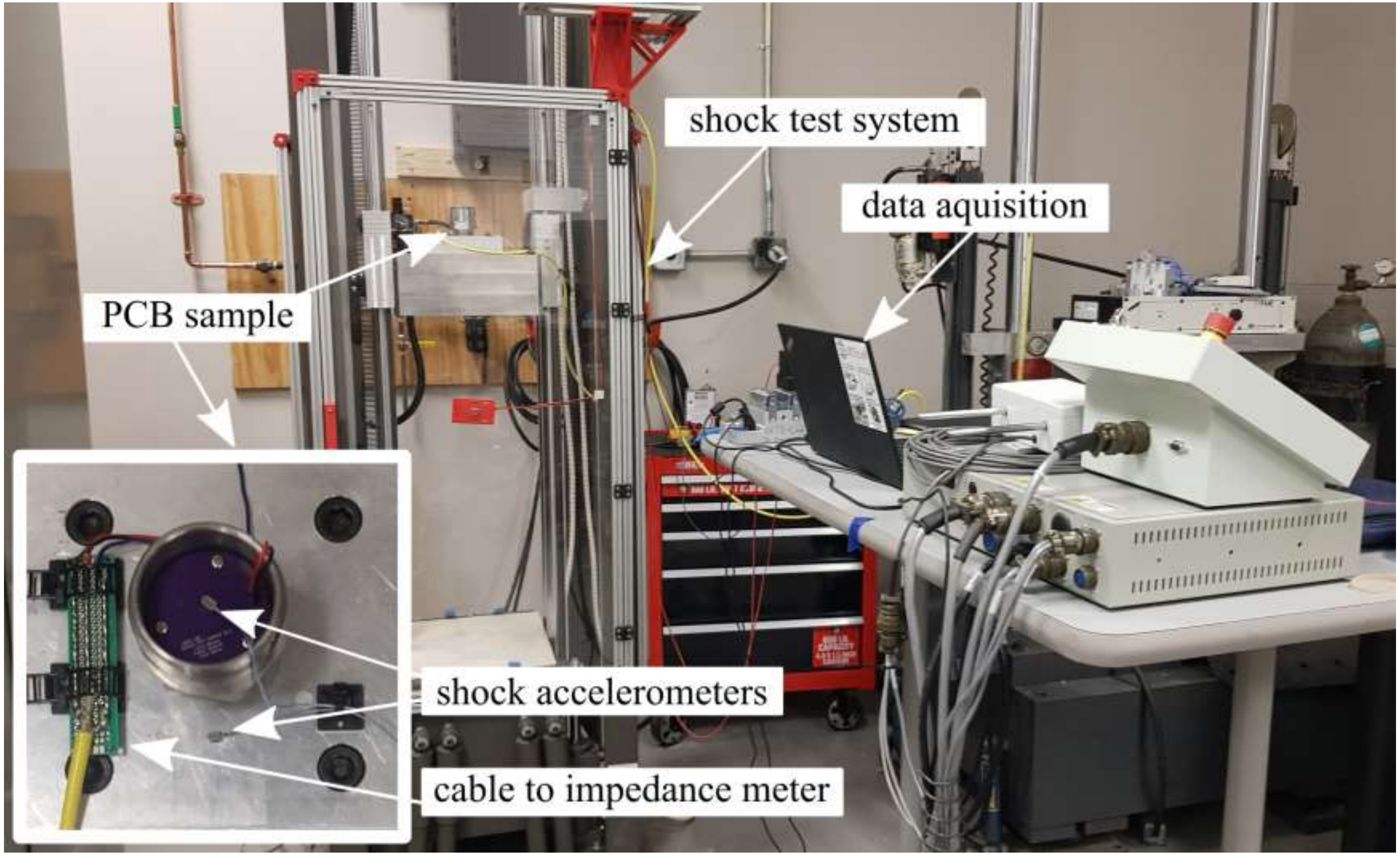
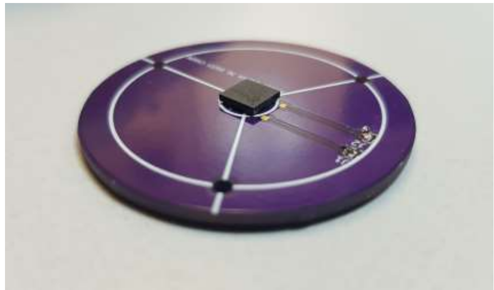
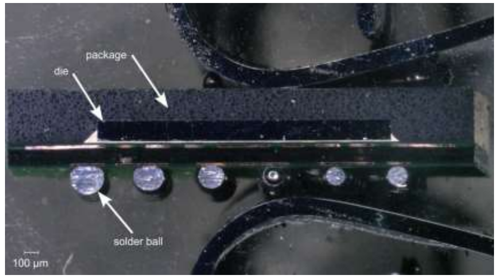
FPGA Implementation (Timing Consideration)

# Experimental System used for Validation



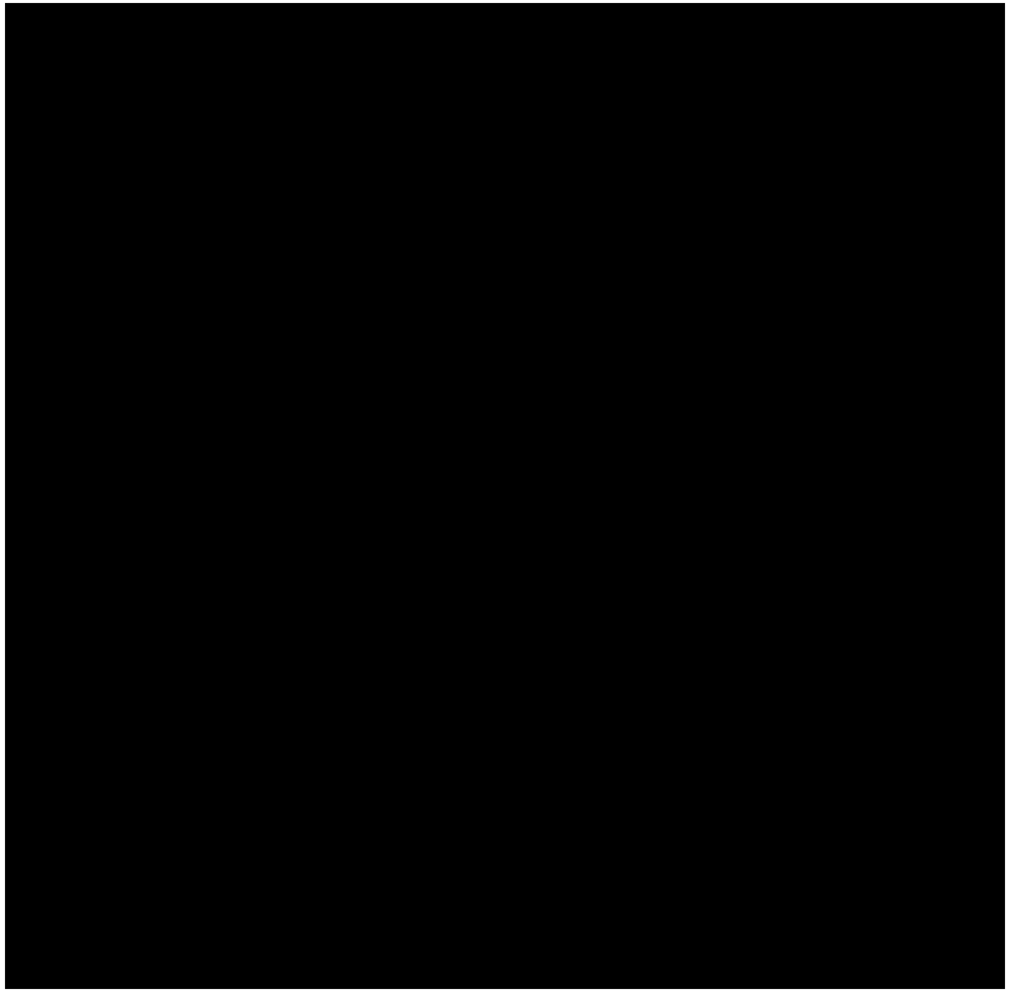



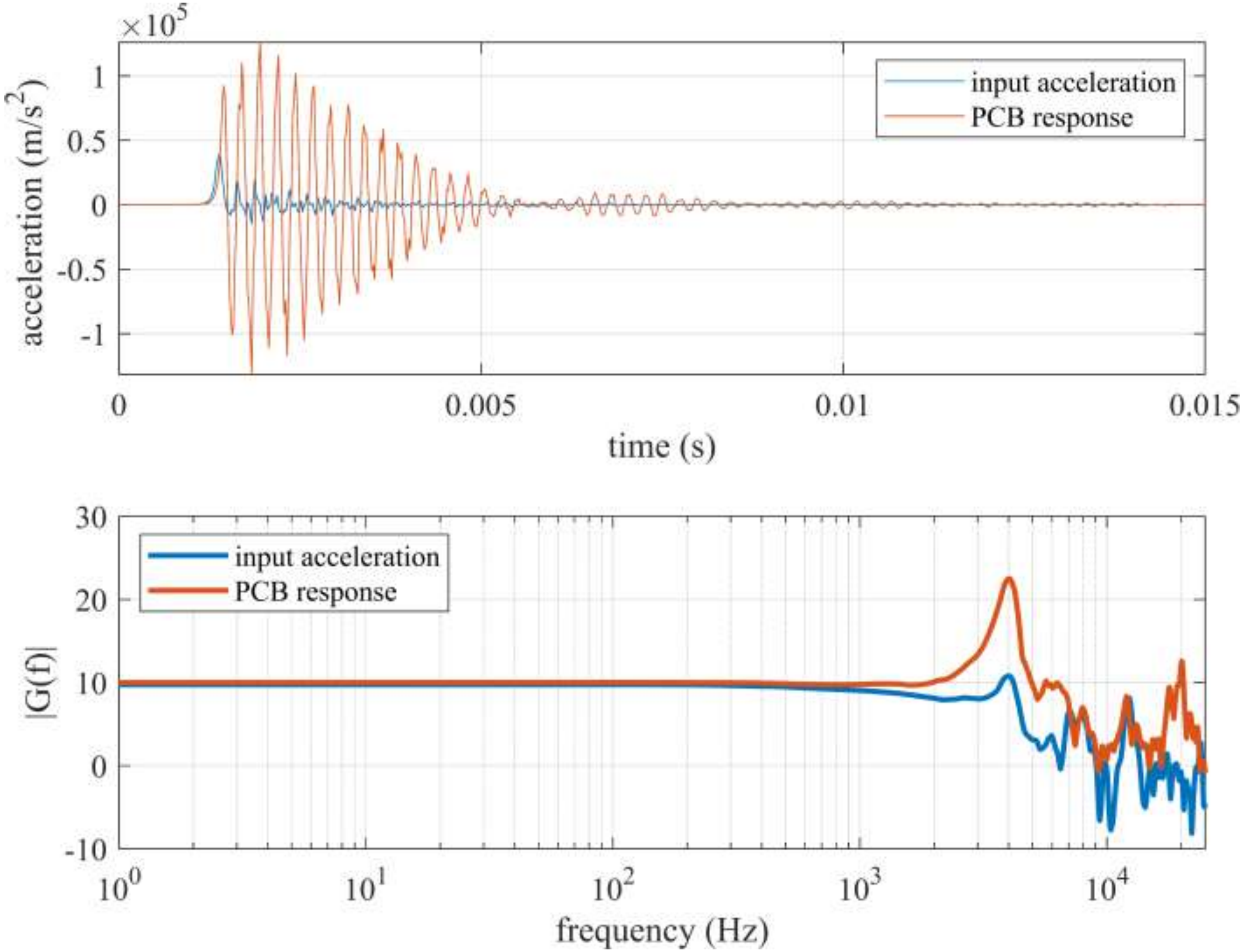



GitHub

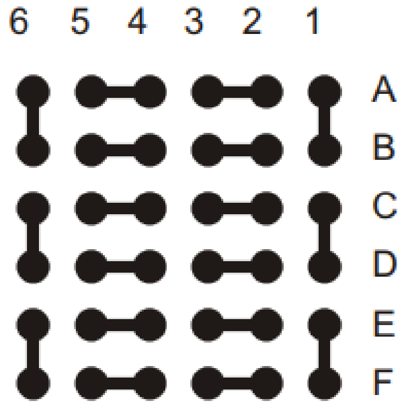
https://github.com/High-Rate-SHM-Working-Group/Dataset-5-Extended-Impact-Testing

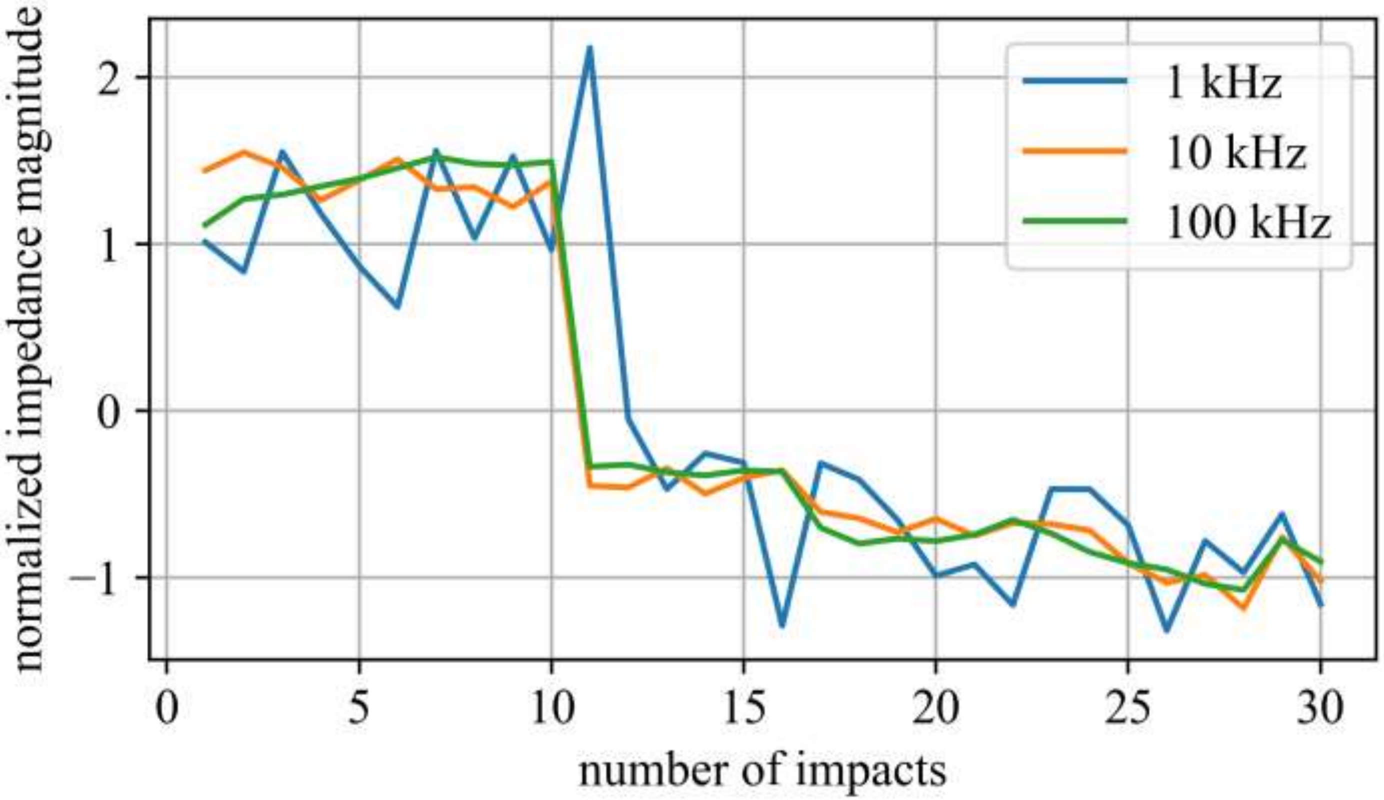
# Experimental System used for Validation

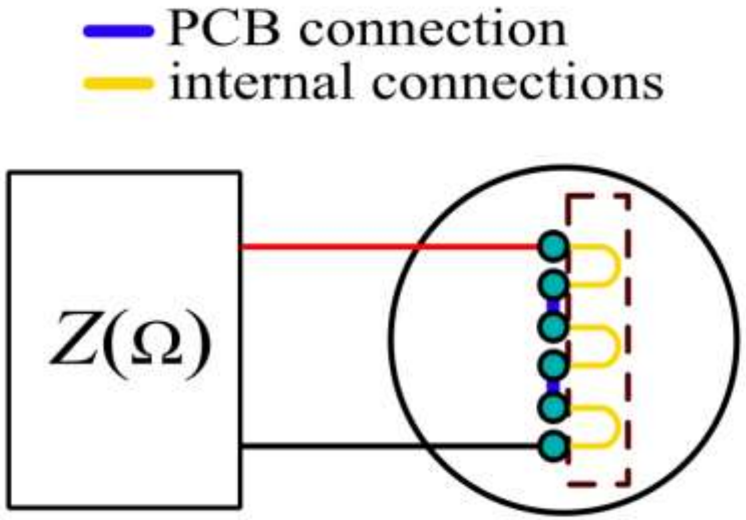




# Experimental System used for Validation

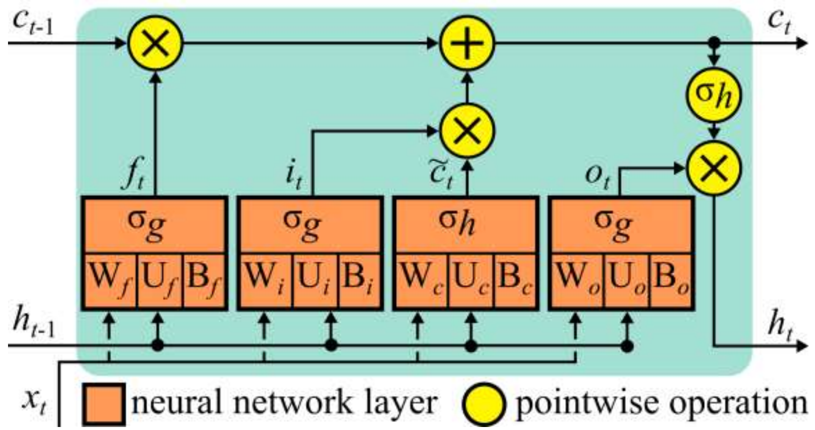



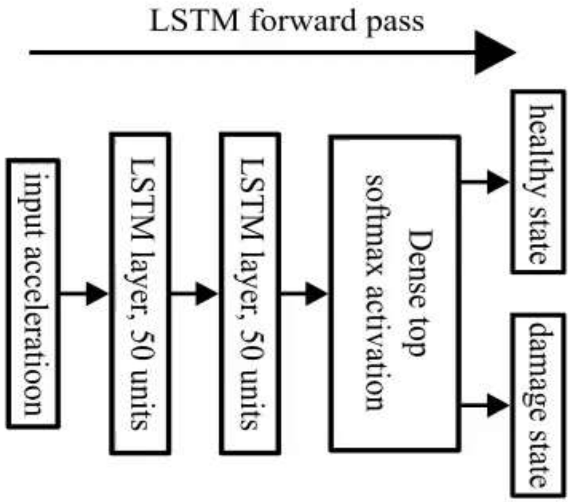



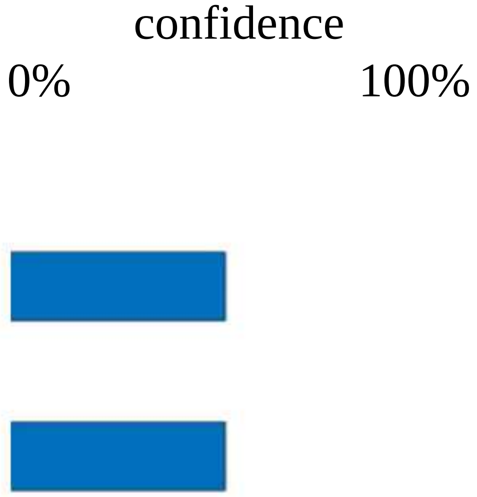
# LSTM-based Real-time State Estimation

In this work:

- 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

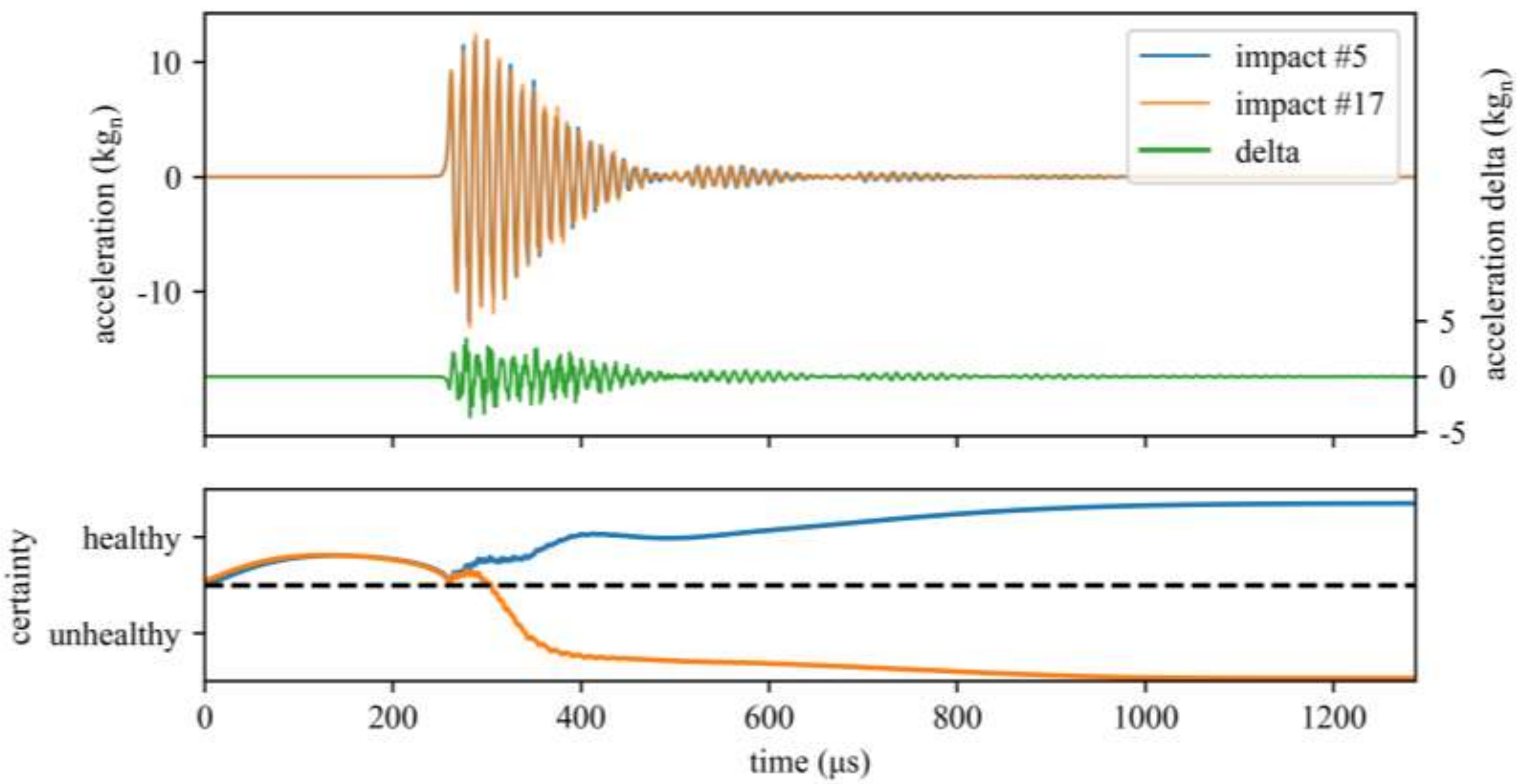


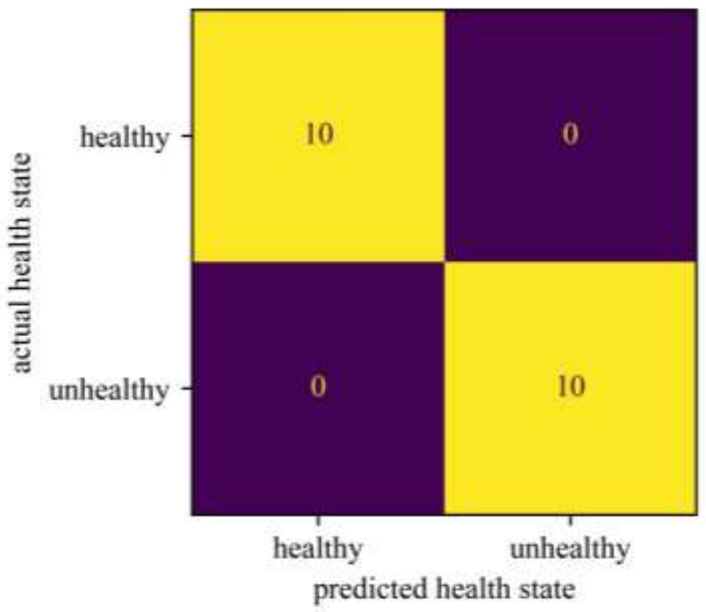



# Model Results

Prediction of survivability of PCB exposed to shock loads



# FPGA Implementation (Timing Consideration)

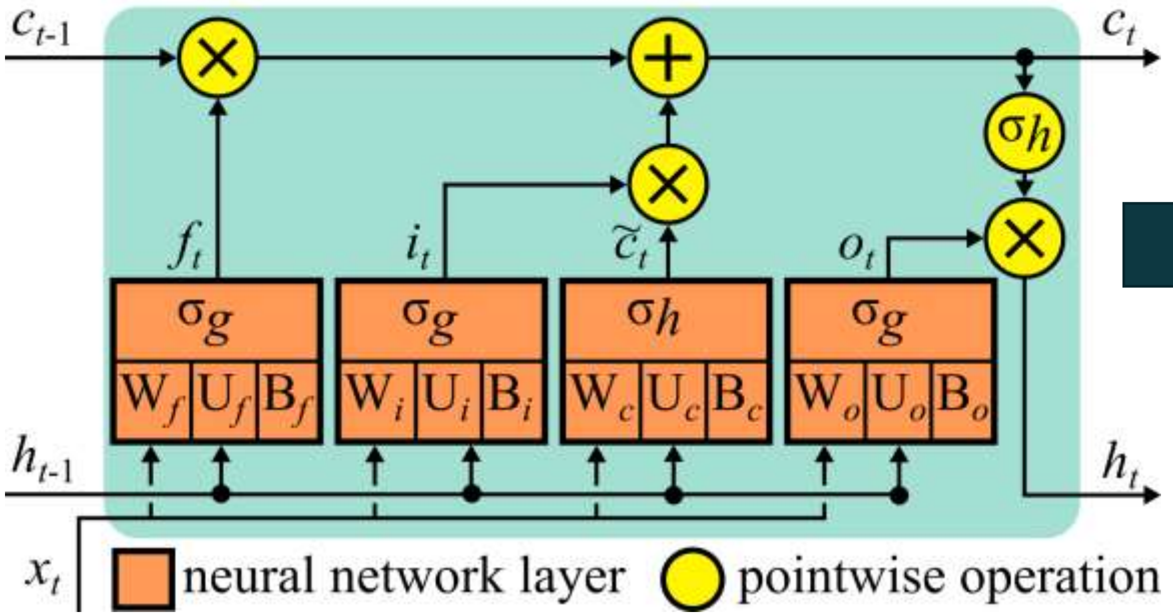
Data Driven Model Updating (Theory and Proof of Concept)

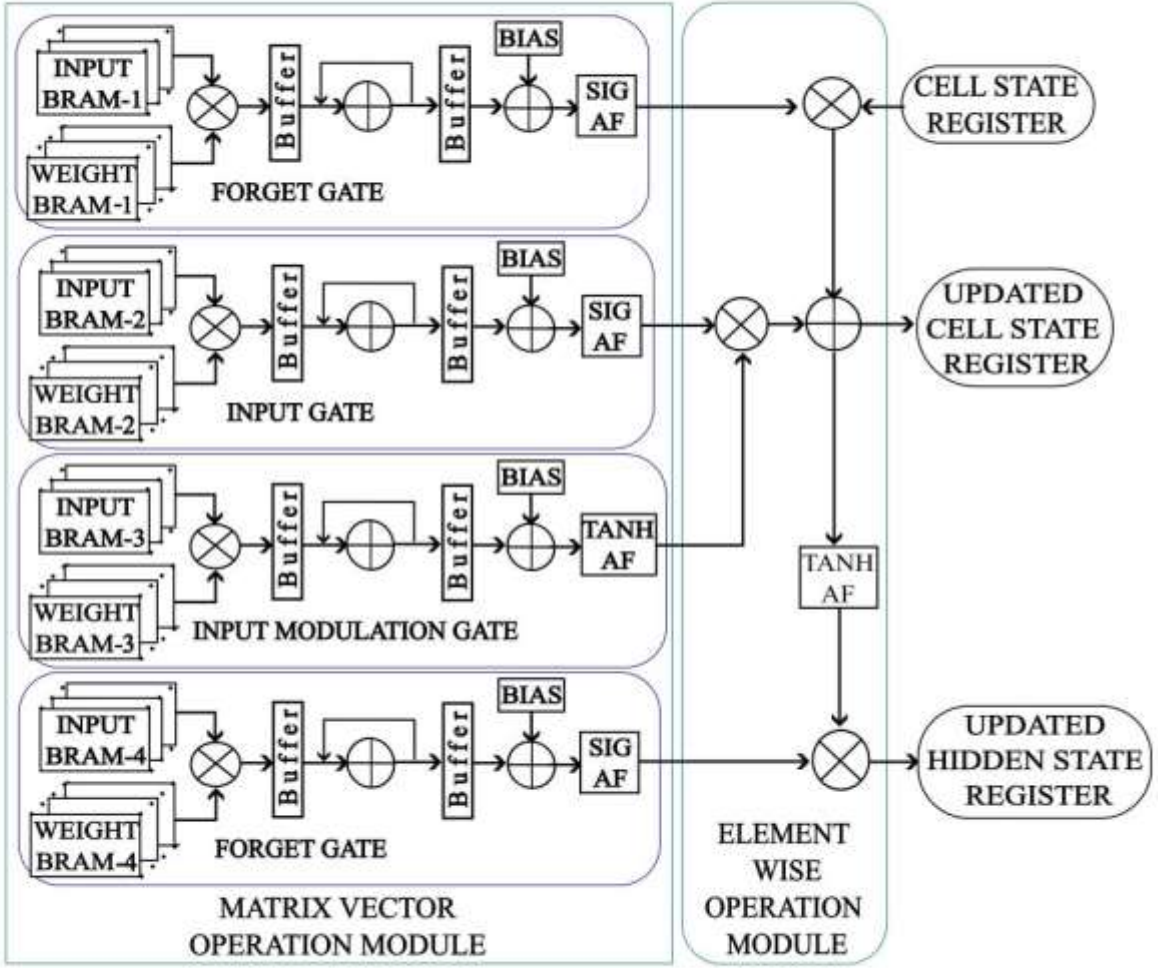
Electronic Components Under Shock (Application)

**FPGA Implementation (Timing Consideration)**

# LSTM deployment on an FPGA

The developed hardware accelerator is split up into the LSTM's gates for deployment.

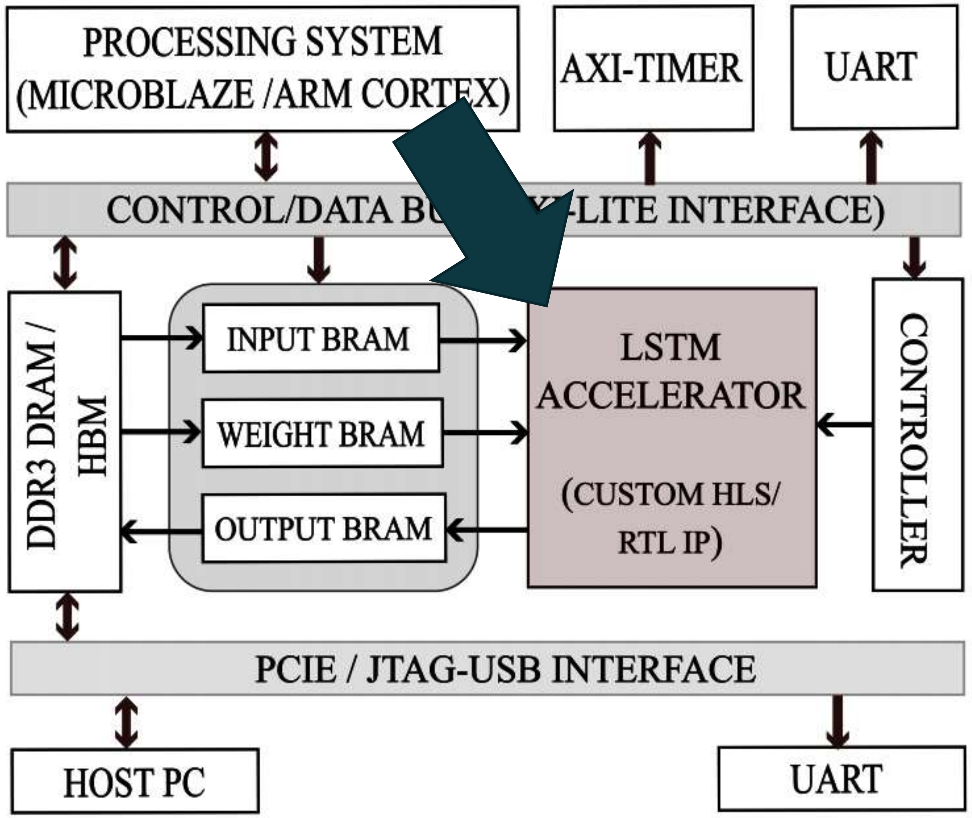


# Custom LSTM Hardware Accelerator

Building a hardware accelerator for deploying LSTMs with a focus on low latency using High-Level Synthesis (HLS).

- Designed in C++ with Vitis HLS, then synthesized into Hardware Description Language (HDL).
- Two main units: Matrix-Vector Operations (MVO) and Element-Wise Operations (EVO).
- Partial or full array partitioning optimizes BRAM usage based on LSTM size.
- Loop pipelining improves parallelization, but BRAM port limits restrict full parallelism.



# Parallelism study

Effect of Parallelism on HDL Design

- LSTM hardware accelerator replacement created in both Hardware Description Language (HDL) and High-Level Synthesis (HLS). HDL exposed more parallelism.
- Software baseline system developed on National Instruments testbed. State prediction output every 500 µs.

| Platform | Bit Precision | LUT (%) | DSP (%) | Highest Level of Parallelism | Fmax (MHz) | Latency ($\mu$S) |
|---|---|---|---|---|---|---|
| Virtex 7 | FP-32 | 28 | 69 | 4 Units | 142 | 5.78 |
| | FP-16 | 39 | 72 | 15 Units | 166 | 2.06 |
| U55C | FP-32 | 11 | 38 | 8 Units | 150 | 2.38 |
| | FP-16 | 9 | 22 | 15 Units | 250 | 1.42 |

# Takeaway

It is possible to use online data-driven models for micro-second tracking of structures during impact.

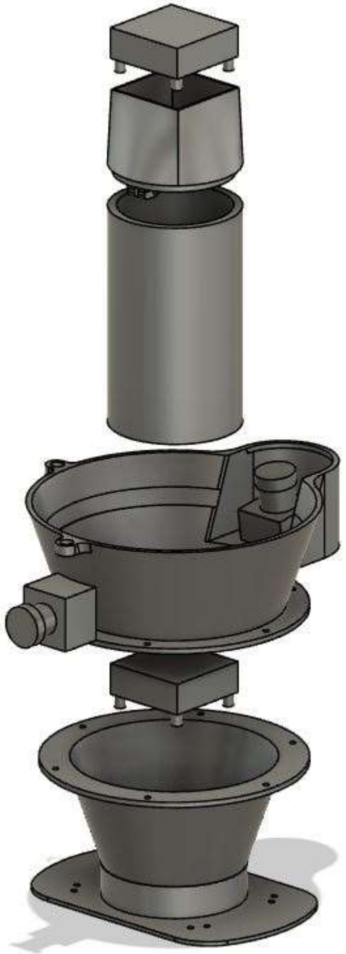
# Part 3: Signal Processing for UAV-deployed Sensors

# Challenges and Innovations in Structural Health Monitoring

- **Current Limitations:** SHM depends on specialized equipment and personnel, reducing speed and flexibility.
- **Deployment Challenges:** Hazardous or aging structures increase cost and safety risks.
- **Need for Rapid SHM:** Real-time insights, autonomous deployment, and wireless communication are essential for efficient monitoring.

# Challenges and Innovations in Structural Health Monitoring

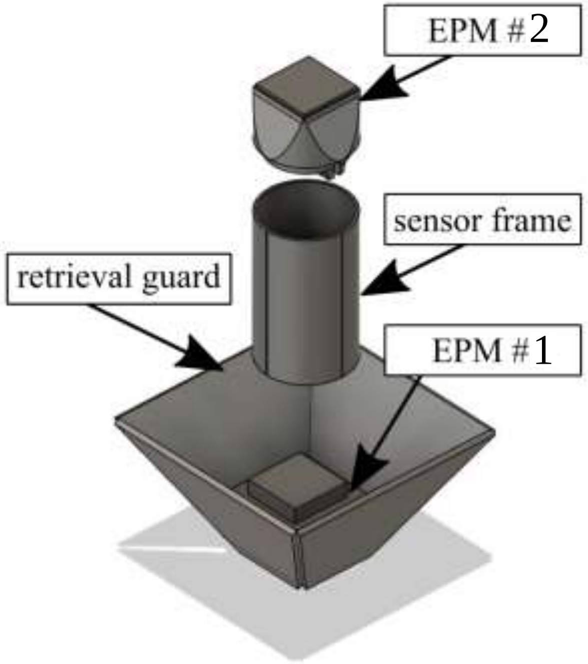
- **Autonomous Deployment:** Fast, precise sensor placement.
- **Real-Time Monitoring:** Continuous data for proactive assessment.
- **Cost & Time Efficient:** Reduces manual inspections.
- **Scalable Solution:** Works for bridges, levees, and more.
- **Enhanced Safety:** Minimizes human exposure.



# Sensor Package

- **Deployment System:** Uses a 3D-printed recovery cone for guided docking
- **Integrated Streaming:** Provides multiple camera views for precise navigation
- **Electropermanent Magnets:** Secure sensor placement and retrieval
- **Error Compensation:** Redundancy measures for safe, reliable operation in complex environments

# Deployment and Retrieval System


| | EMP #1 | EPM #2 |
|---|---|---|
| Deployment | On | Off |
| Retrieval | Off | On |

# Driving Challenges in UAV-deployed Sensors

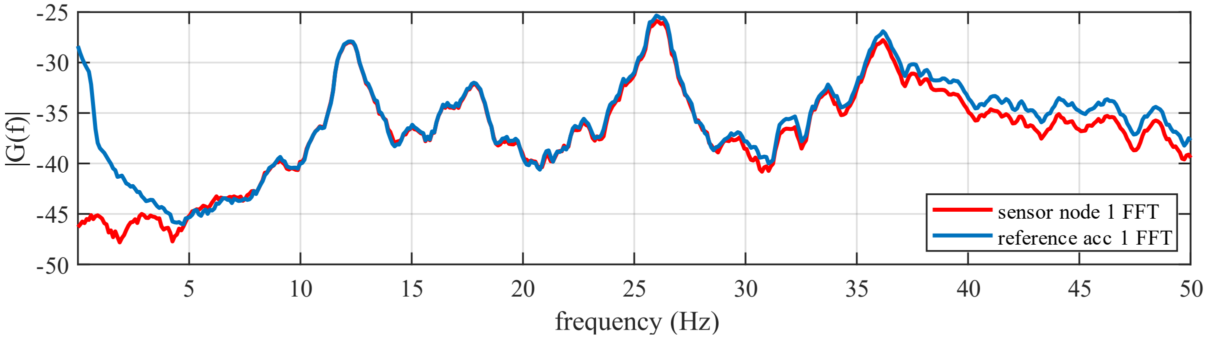
Driving Challenges in UAV-deployed Sensors

UAV and Sensor Hardware

Edge Processing of Sensor Signal

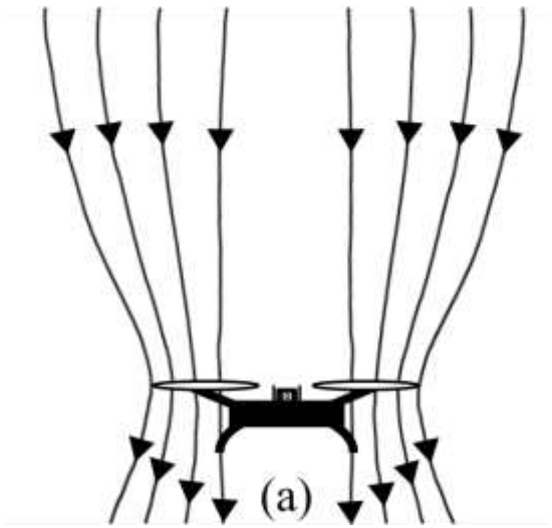
# Our Solution – UAV-Deployable Sensor Package

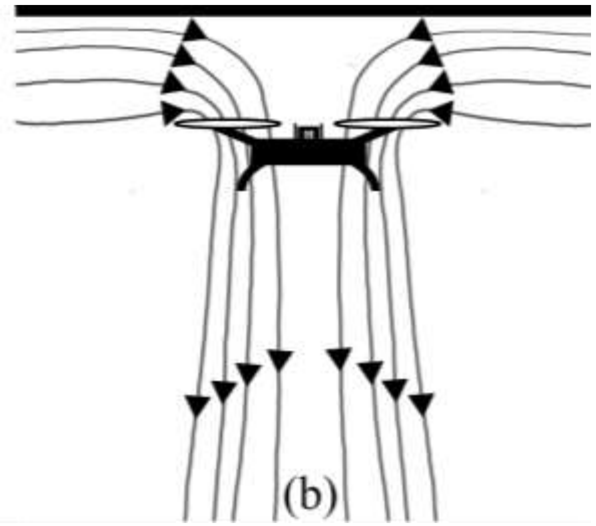
- **Rapid Aerial Sensor Deployment:** Designed for quick, efficient sensor placement in SHM scenarios
- **Enhanced Spatial Awareness:** Multiple camera views for precise navigation, docking, and sensor deployment
- **Electropermanent Magnetic Docking:** Secure attachment with a recovery cone for guided docking
- **Built-in Redundancy:** Safety and reliability features to ensure successful deployments



# Understanding the Ceiling Effect in UAVs

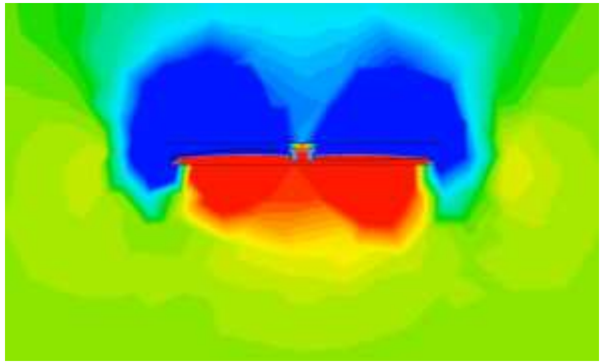
- **Definition:** The ceiling effect occurs when a propeller operates near a barrier, like a ceiling, altering the airflow and making lift more efficient.
- **Cause:** Impeded airflow above the propeller leads to a pressure drop, creating an increase in lift.
- **Impact on Control:** The UAV operator may notice sudden, unexpected lift or reduced control near the ceiling.

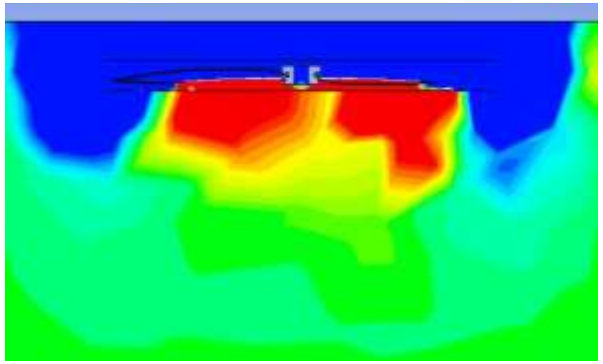



propeller in open air

propeller under ceiling effect





# Challenges in Human-Operated Flight for Sensor Deployment in SHM

- **Ceiling Effect Variability:** Sudden lift changes near ceilings
- **Pilot-Induced Instability:** Oscillations from manual control
- **Signal Interference:** Issues near metal structures
- **Line of Sight Limitations:** Restricted visibility impacts precision

**No researchers were harmed during this endeavor!**

# UAV and Sensor Hardware

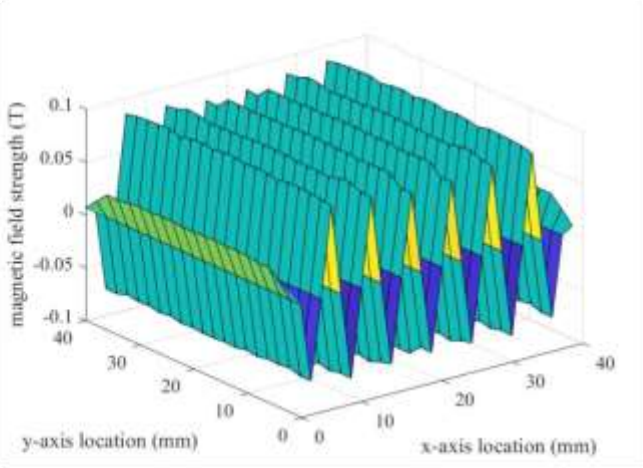
Driving Challenges in UAV-deployed Sensors

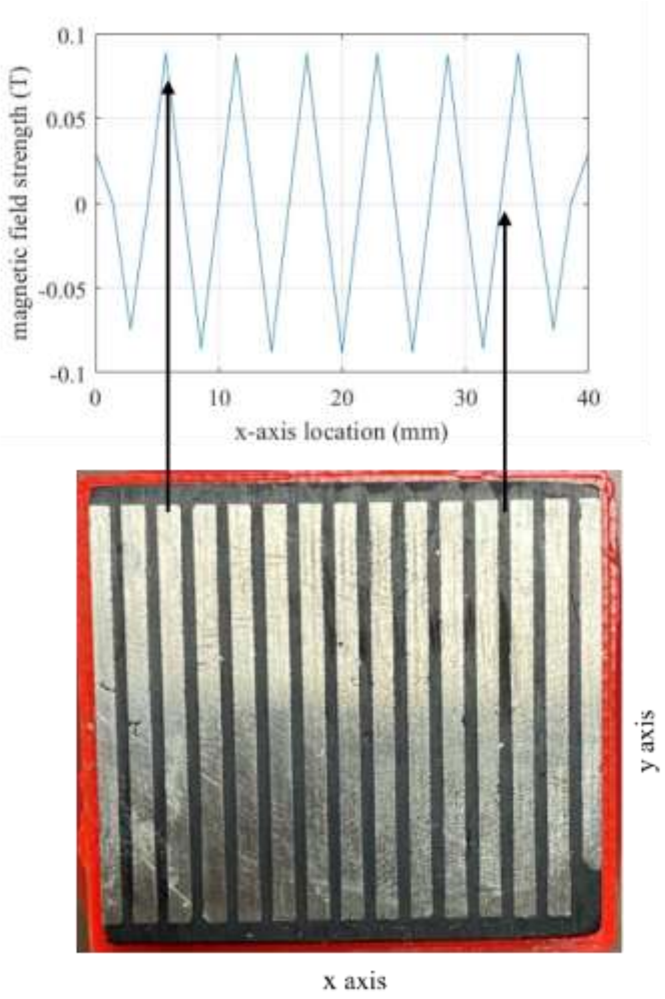
UAV and Sensor Hardware

Edge Processing of Sensor Signal

# Deployment and Retrieval System

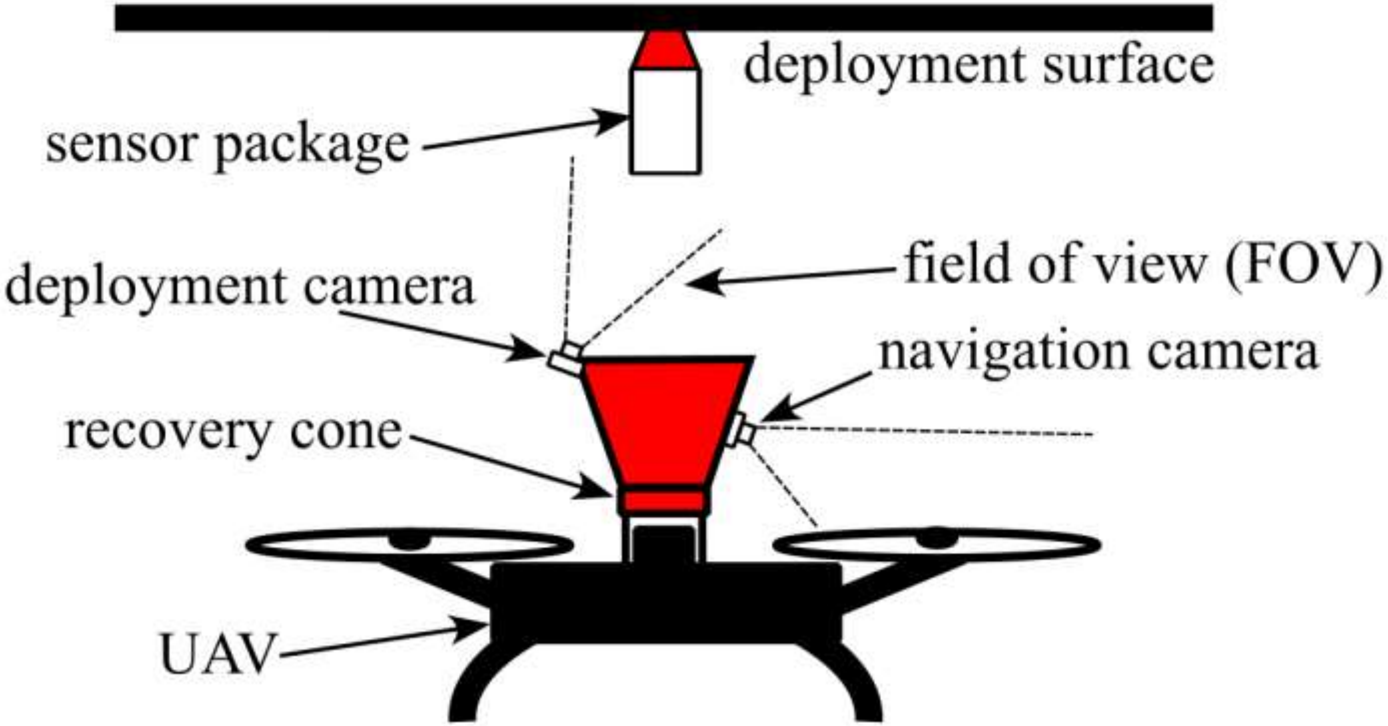
- **Electromagnetic Activation:** Pulse-activated magnetic polarity control
- **Energy-Efficient:** Holds magnetic state without continuous power
- **Versatile Applications:** Ideal for clamping, lifting, and sensor deployment
- **Stable Magnetic Configuration:** Maintains position securely using South-South or South-North fields




# Camera-Assisted Deployment

- **Multi-Camera Setup:** Provides real-time spatial awareness for precise navigation.
- **Target Identification:** Assists in locating the sensor package with visual feedback.

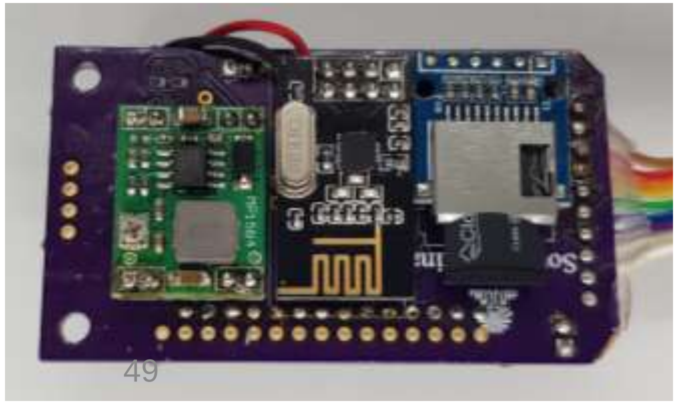


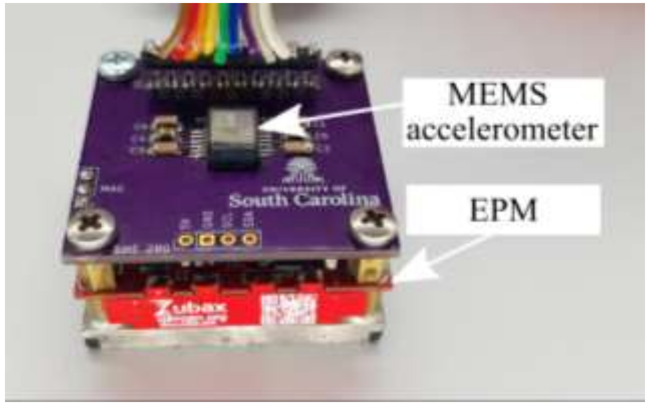
# In-flight Data Collection

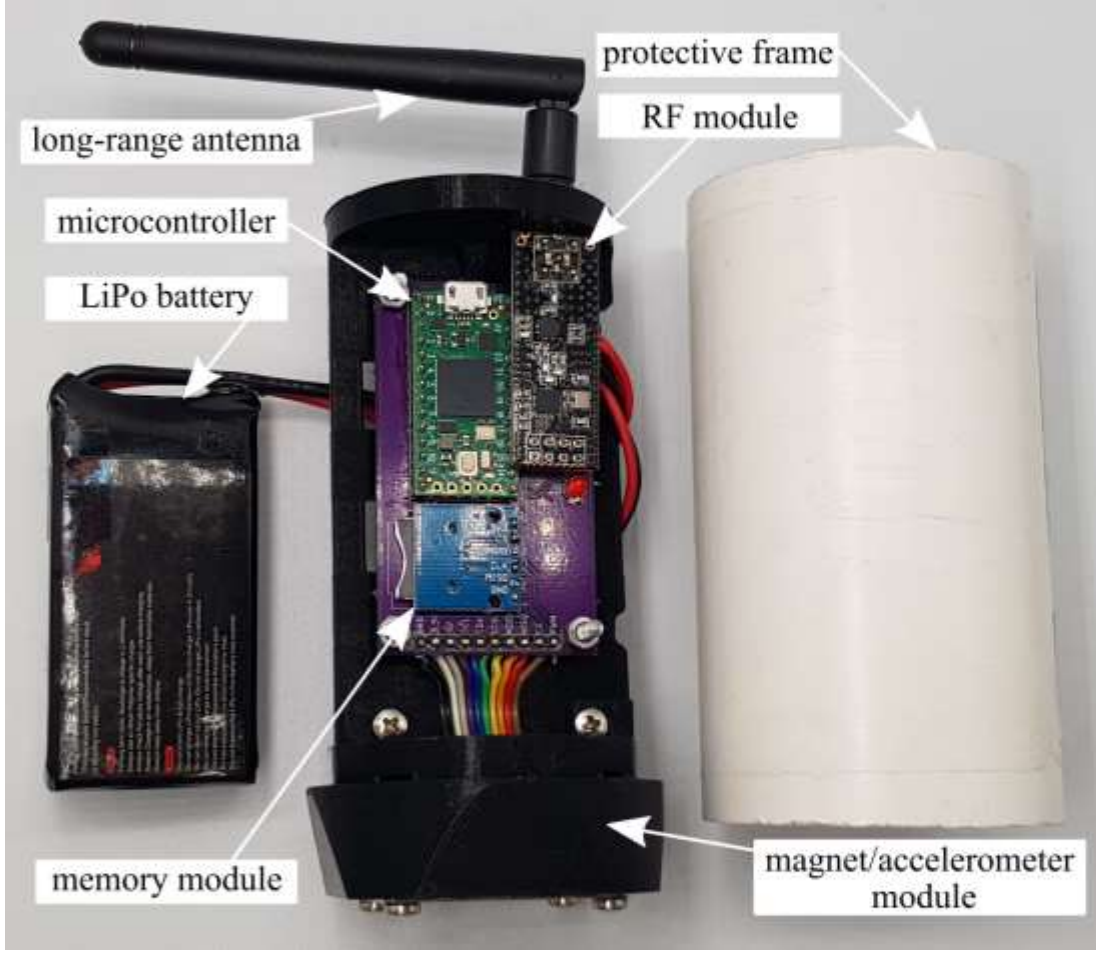
- **Accurate Alignment:** Guides the UAV to align the recovery cone with the sensor package.
- **Foundation for Autonomy:** Key step towards a fully autonomous UAV system.
- **End-to-end Machine Learning Control:** Currently developing end-to-end methods for the autonomous retrieval of sensor packages.

# Sensor Hardware and Onboard Systems

- **Robust Design:** Aerially deployable with noninvasive EPM docking
- **Reliable Operation:** Power management, nonvolatile memory, and wireless communication
- **Sensing:** Accelerometer up to 28 kS/s; frame minimizes transmissibility loss

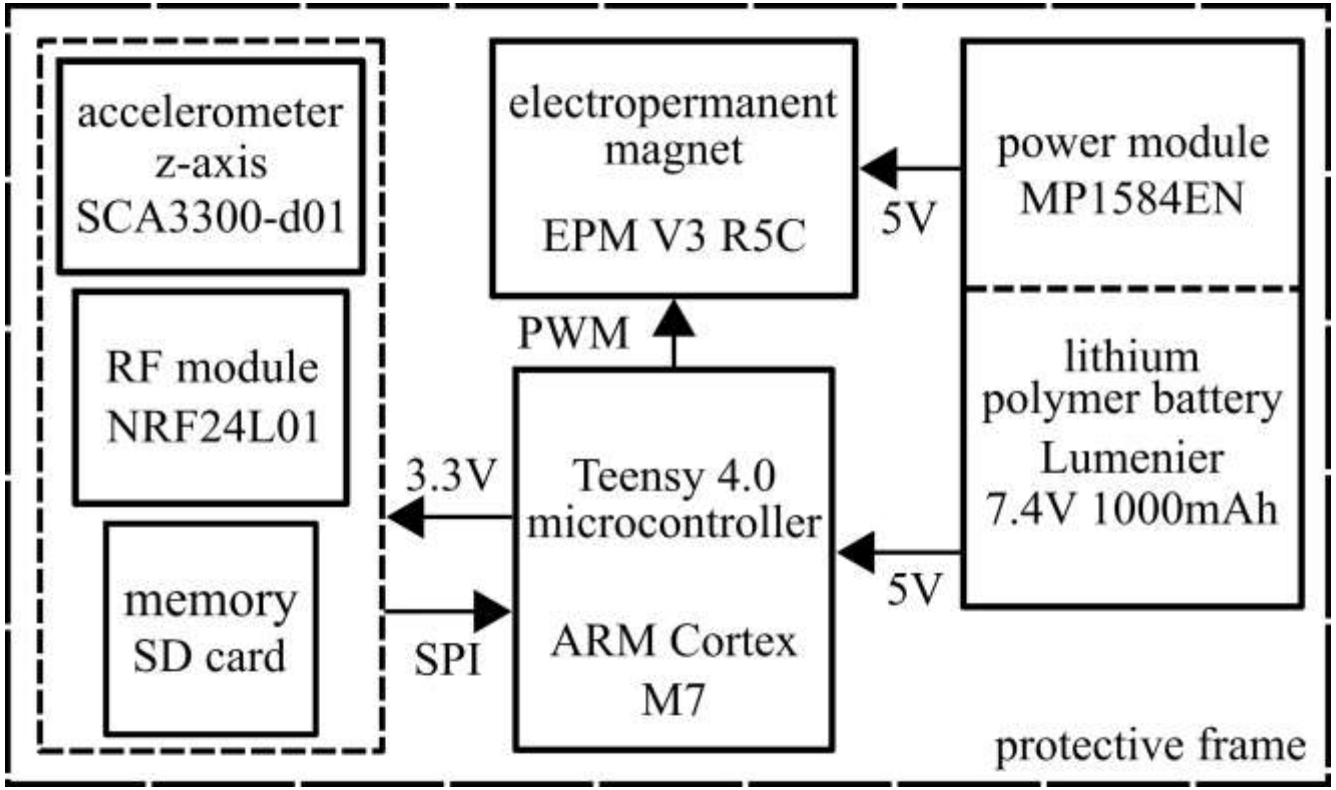




# Sensor Package System Architecture

- **Core Processing:** Teensy 4.0 microcontroller (ARM Cortex M7) with SD card for data storage
- **Communication:** High-sensitivity accelerometer and RF module for real-time data and commands

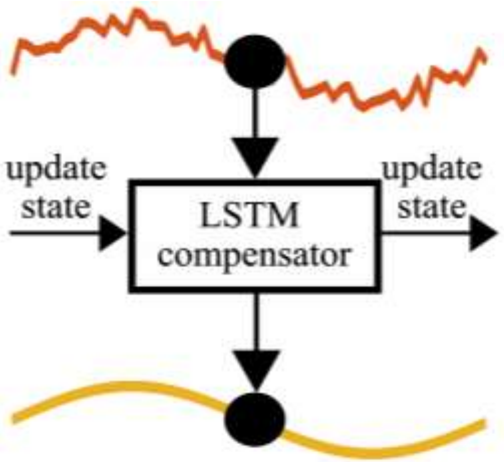


# Edge Processing of Sensor Signal

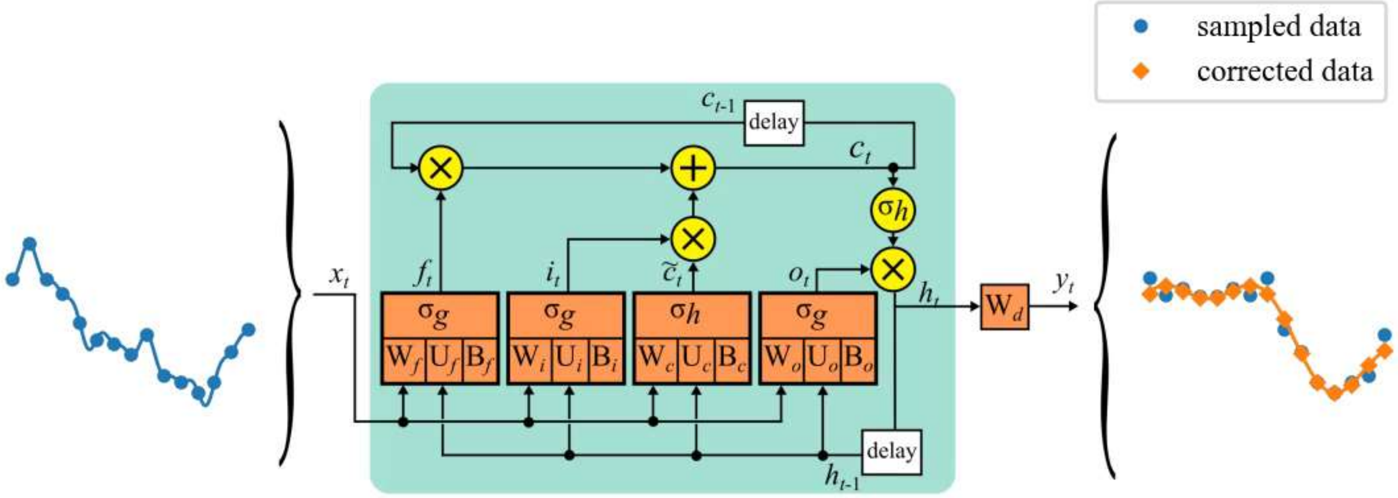
Driving Challenges in UAV-deployed Sensors → UAV and Sensor Hardware → Edge Processing of Sensor Signal

# LSTM-Based Signal Compensation Process

- Model training procedure
- Supervised learning method
- Assumptions:
  - Sampling rates were set equal (400 S/s)
  - Zero phase between the two sensors
  - Bandwidth of interest to be < 10 Hz
- Model chosen is a single-layer 50-unit LSTM
- Backpropagation is done online every 400 datapoints (1 second)




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



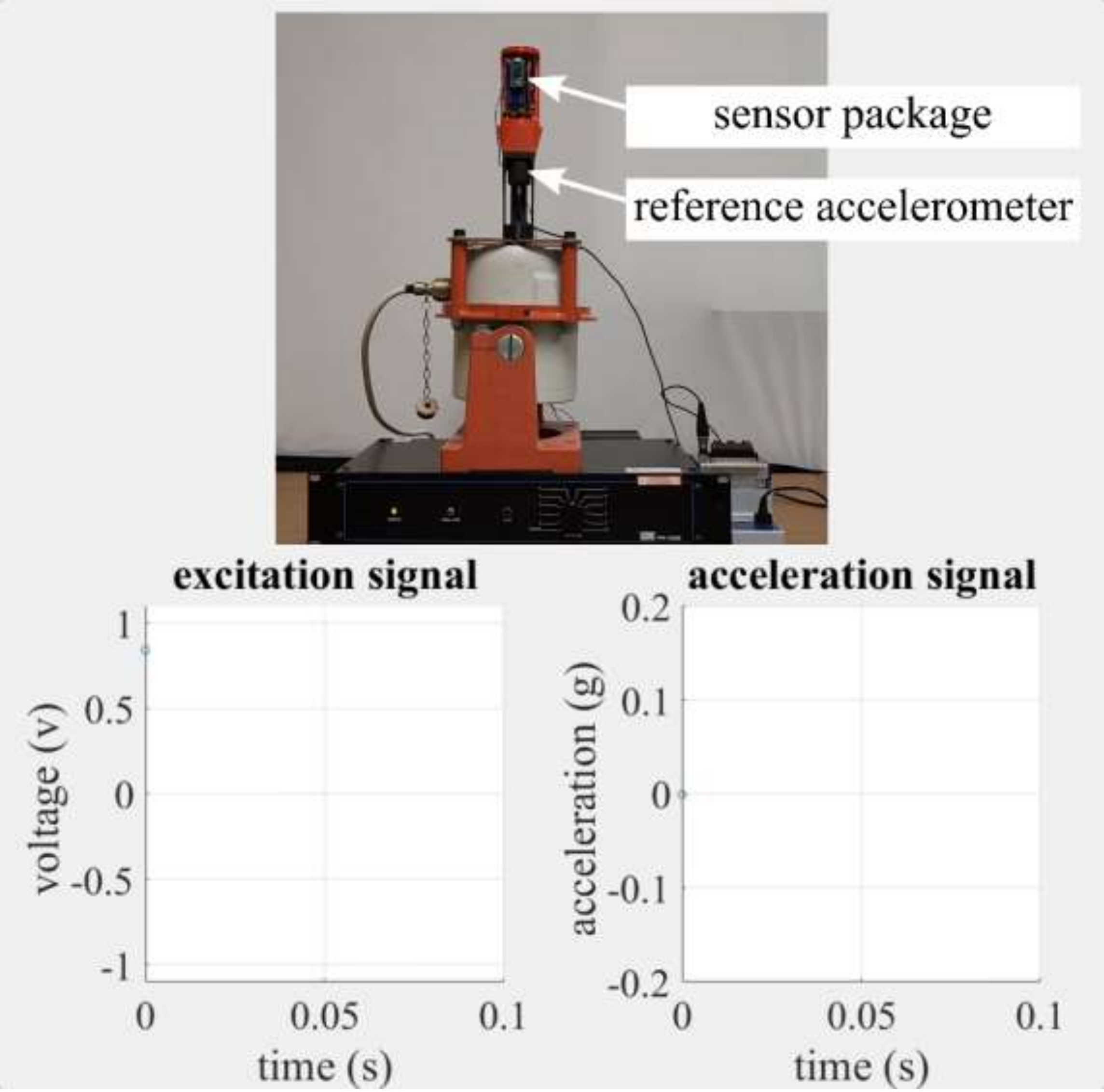
# Signal Conditioning and Error Compensation

- Chirp excitation is fed into the electromagnetic shaker using an analog output module
- A data acquisition is used to record reference acceleration
- A digital trigger is set to synchronize both the reference accelerometer and sensor package
- Various dynamic ranges were used to expand the training range of the LSTM model

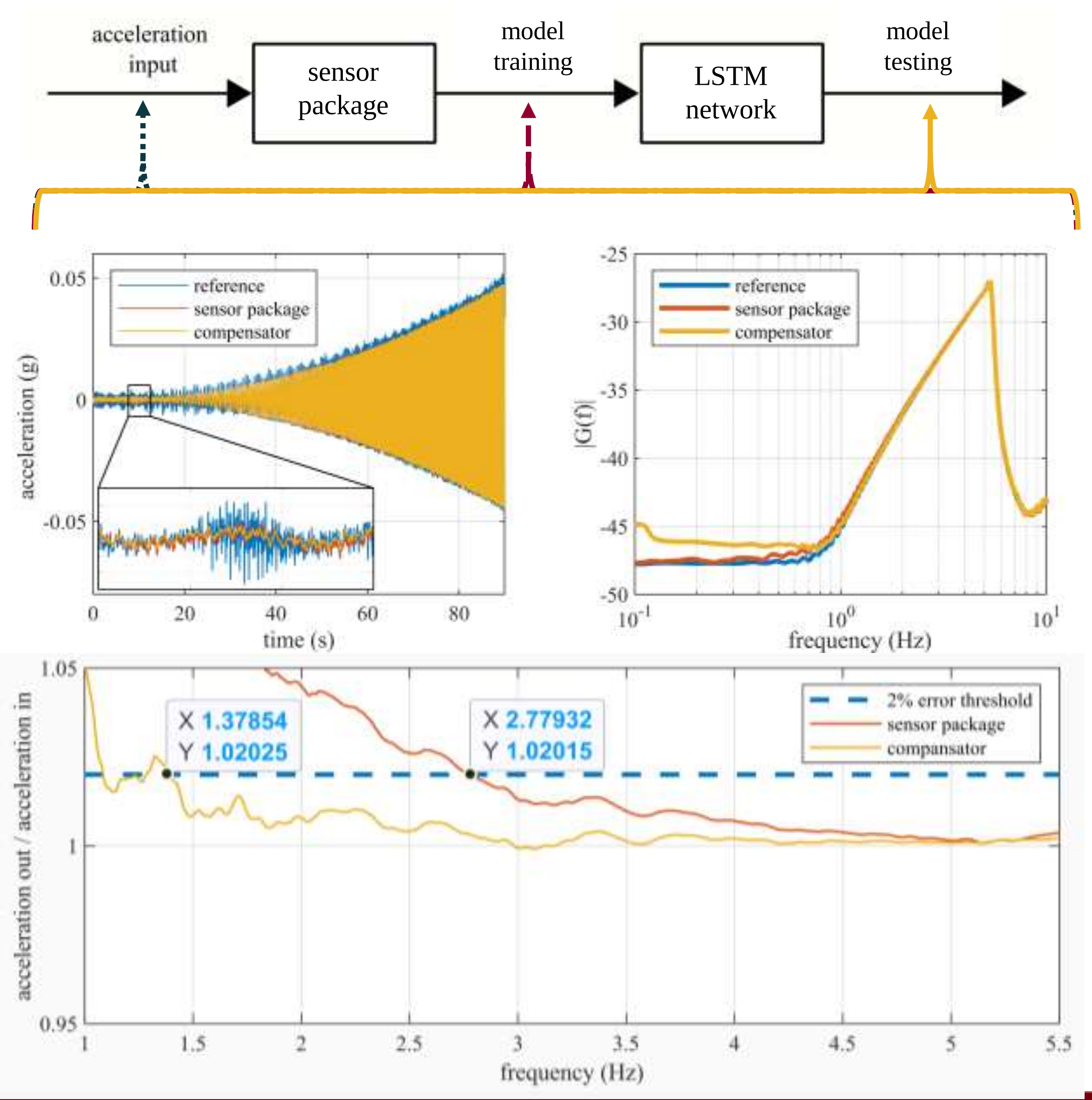
$$x(t) = \sin\left(2\pi\left(\frac{f_{\text{end}} - f_{\text{start}}}{2(\text{test time})}t^2 + f_{\text{start}}t\right)\right)$$

$$\text{SNR}_{\text{dB}} = 10\log_{10}\left(\frac{\sum_{i=1}^{\text{data length}}(\text{signal}(i))^2}{\sum_{i=1}^{\text{data length}}(\text{noise}(i))^2}\right)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{\text{data length}}(\text{truth(i)} - \text{prediction(i)})^2}{\text{data length}}}$$



# LSTM Performance




## LSTM compensator performance

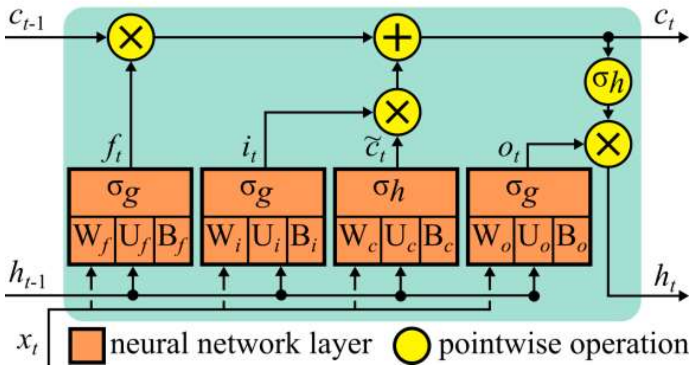
- For testing a chirp excitation in 0-5 Hz is used
- $SNR_{dB}$ enhancement of 9.34%
- RMSE reduction of 19.66%
- Usable bandwidth (< ±2%) is shown to increase form 2.78 Hz to 1.34 Hz
- An overall increase in gain below 0.9 Hz due to training bias

| testing | $SNR_{dB}$ | RMSE |
|---|---|---|
| sensor package | 17.26 dB | $1.795\times10^{-3}$ |
| LSTM compensator | 18.88 dB | $1.442\times10^{-3}$ |
| % improvement | 9.34% | 19.66% |

# Conclusion

The ARTS-Lab is a multidisciplinary research lab tackling challenges in control and edge computing.

- High-rate ML at the edge enables structural model updates in microseconds.
- Online signal compensation enhances data usability for UAV-deployed sensors in structural health monitoring.




# Acknowledgement

This material is based upon work supported by the Air Force Office of Scientific Research (AFOSR) through award no. FA9550-21-1-0083. This work is also partly supported by the National Science Foundation Grant numbers 1850012, 1956071, 2152896, and 2237696. The support of these agencies is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors, and they do not necessarily reflect the views of the National Science Foundation or the United States Air Force.



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# DISCUSSION

## Hardware Keeps the Engineer Honest

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