UAV-deployable sensing network for rapid structural health monitoring

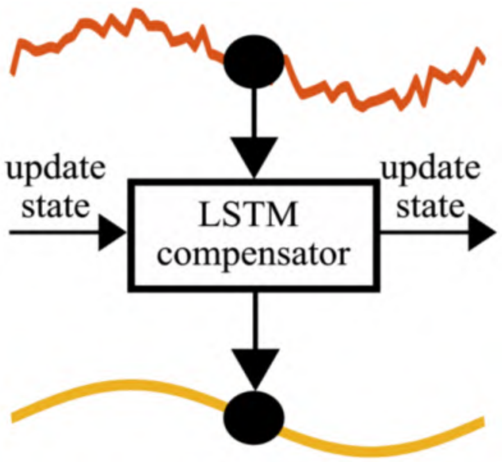
Joud Satme; Department of Mechanical Engineering

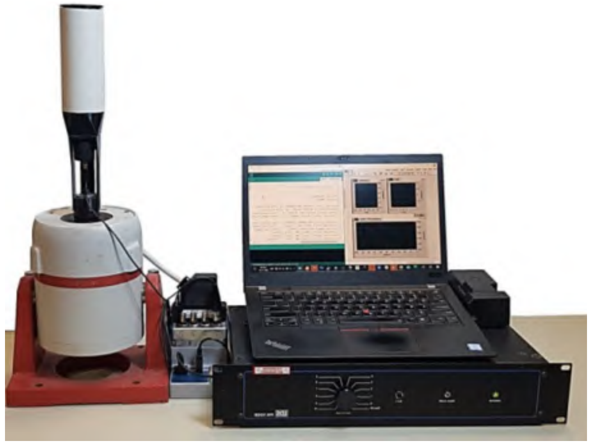
UNIVERSITY OF
SOUTH CAROLINA

Methodology
Experimentation
Results and Discussion
Future work

Outline

- Introduction:
  - project overview and problem statement
  - rapid structural health monitoring
  - technical challenges
- Methodology:
  - deployment and retrieval system
  - sensor hardware and onboard systems
  - signal conditioning and error compensation
  - wireless sensing network
- Experimentation: Case study for using UAV-deployable wireless sensor network for mode detection
- Results and Discussion:
  - time and frequency response of a test structure
  - sensing system experimental challenges
  - system overview
- Future work:
  - edge computing implementation
  - autonomous UAV delivery





Introduction

- Project overview and problem statement:

With Environmental disasters increasing in magnitude and frequency due to climate change, the safety of infrastructure following extreme weather events becomes of a concern.

Maintaining rapid structural assessment capabilities in the aftermath of extreme weather conditions is essential to disaster resilience and the longevity of critical infrastructure.

Structural health monitoring systems currently operational are pushed to their limits due to the need for safer, faster, and more cost-effective solutions to the challenge of large-footprint, high-flexibility sensing for rapid SHM applications.

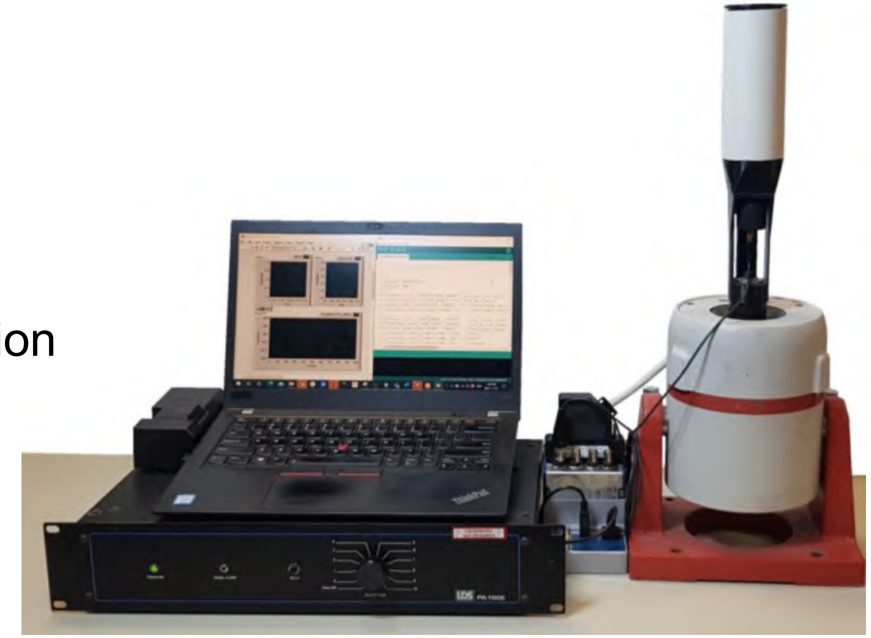
- Rapid structural health monitoring:

Real-time data-driven insights into infrastructure condition with the integration of novel technologies.

  - role of uncrewed vehicles
  - wireless systems for command and communication
- Technical challenges:
  - sensor placement and delivery
  - signal degradation due to mechanical transmissibility loss
  - wireless network triggering latency and error handling

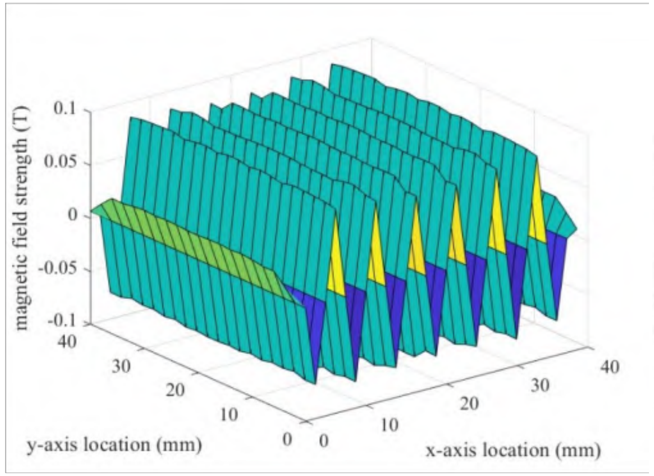
Methodology:

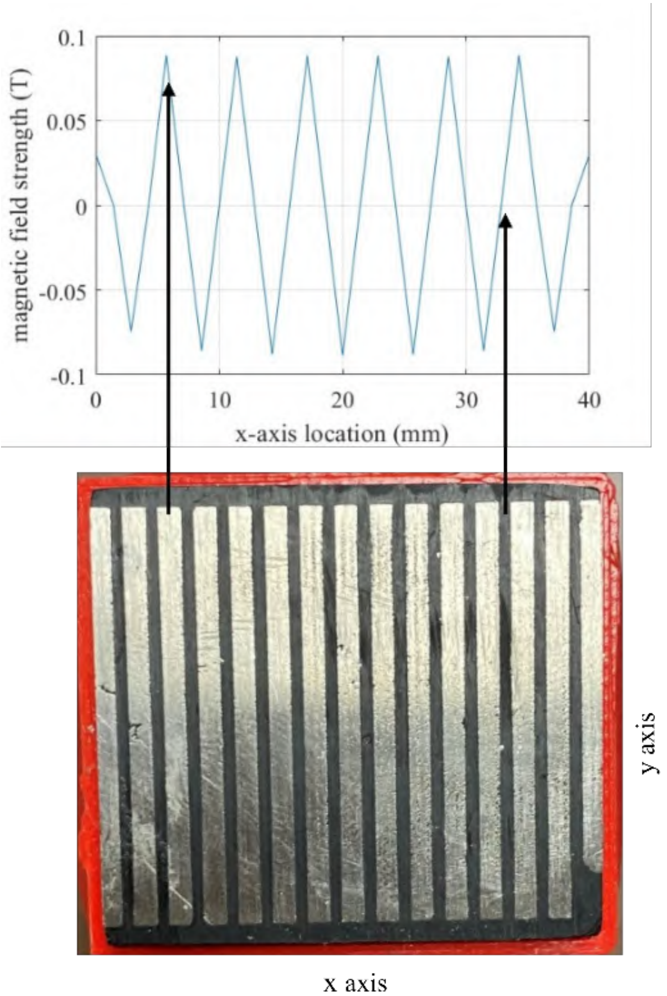
- deployment and retrieval system
- sensor hardware and onboard systems
- signal conditioning and error compensation
- sensing network for structural mode detection



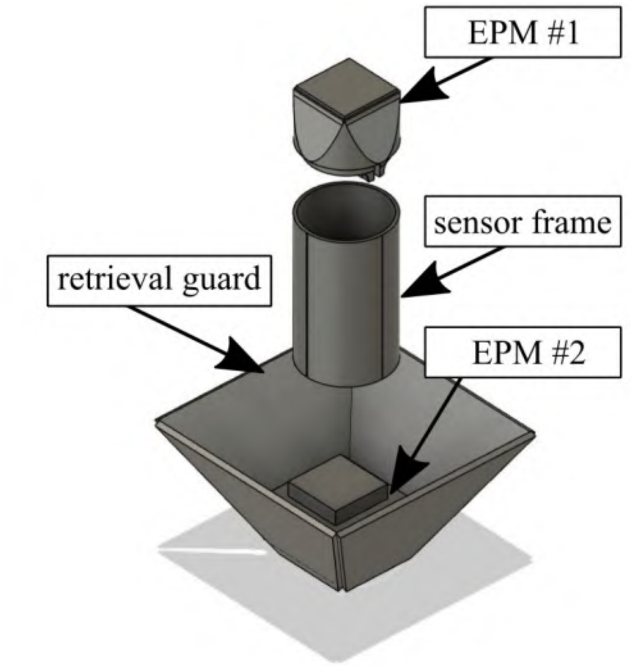
Deployment and retrieval system

- Electromagnetic Activation:
  A brief electric pulse is applied that alters magnetic polarity.
- Energy-Efficient:
  Does not require a constant power to maintain magnetic state, making them energy-efficient.
- Versatile Applications:
  Used in tasks like clamping, lifting, and holding
  Optimal for areal deployment of sensors





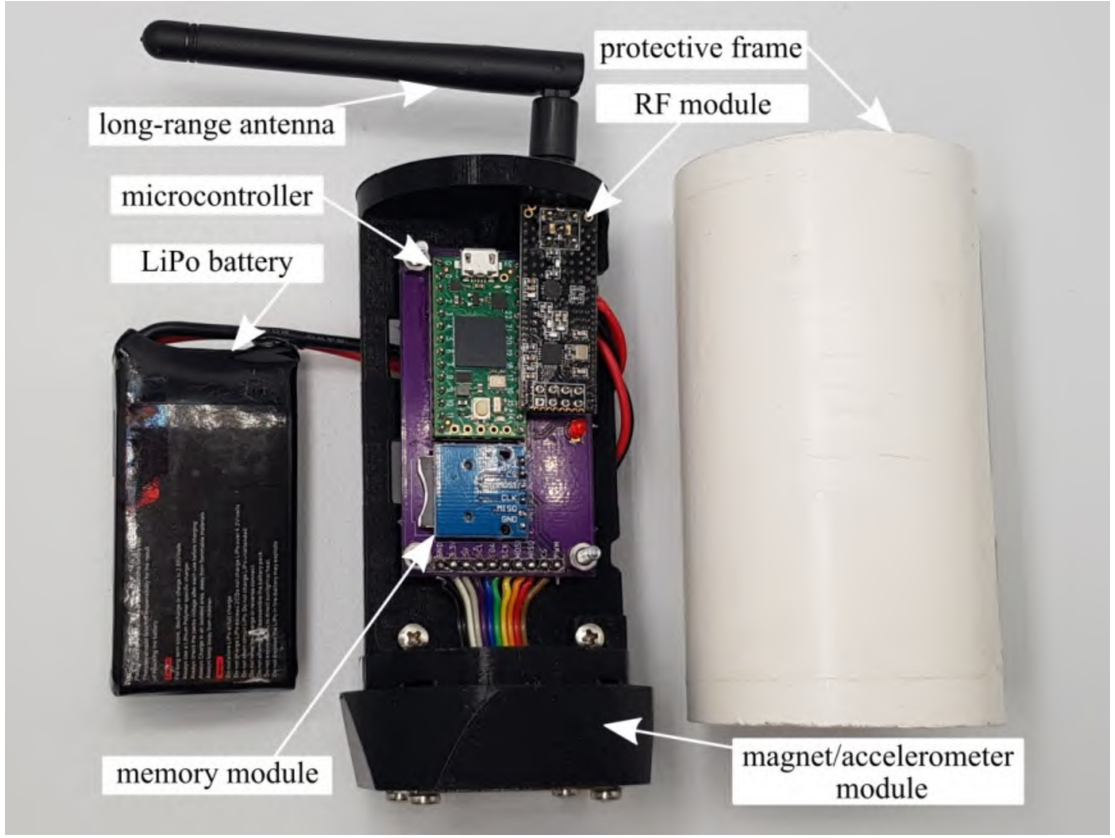
Deployment and retrieval system

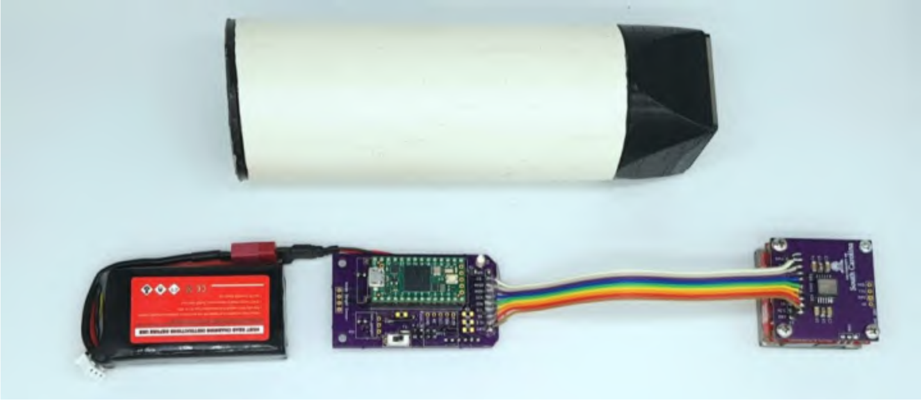


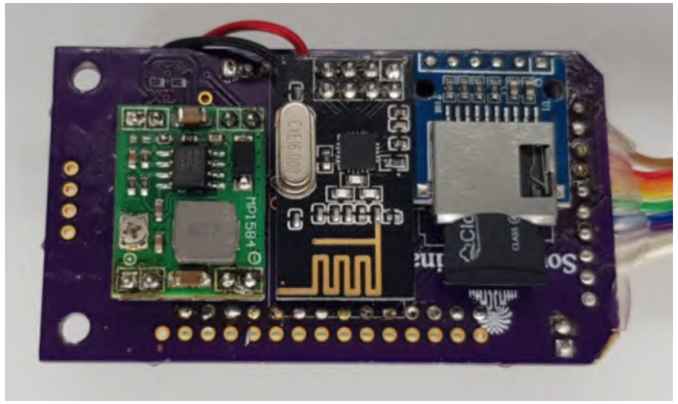
	EMP #1	EPM #2
Deployment	On	Off
Retrieval	Off	On

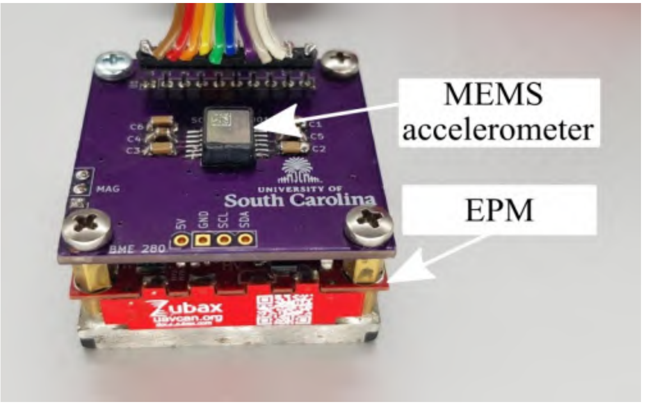
Sensor hardware and onboard systems

- Features:
  - High-mobility robust sensor node
  - Aerially deployable
  - Noninvasive docking utilizing EPM
  - Power management for long deployment periods
  - Nonvolatile memory storage
  - Wireless system for commands and communication
  - Accelerometer maximum sampling rate 28 kS/s.
  - Sensor frame designed to minimize transmissibility loss.



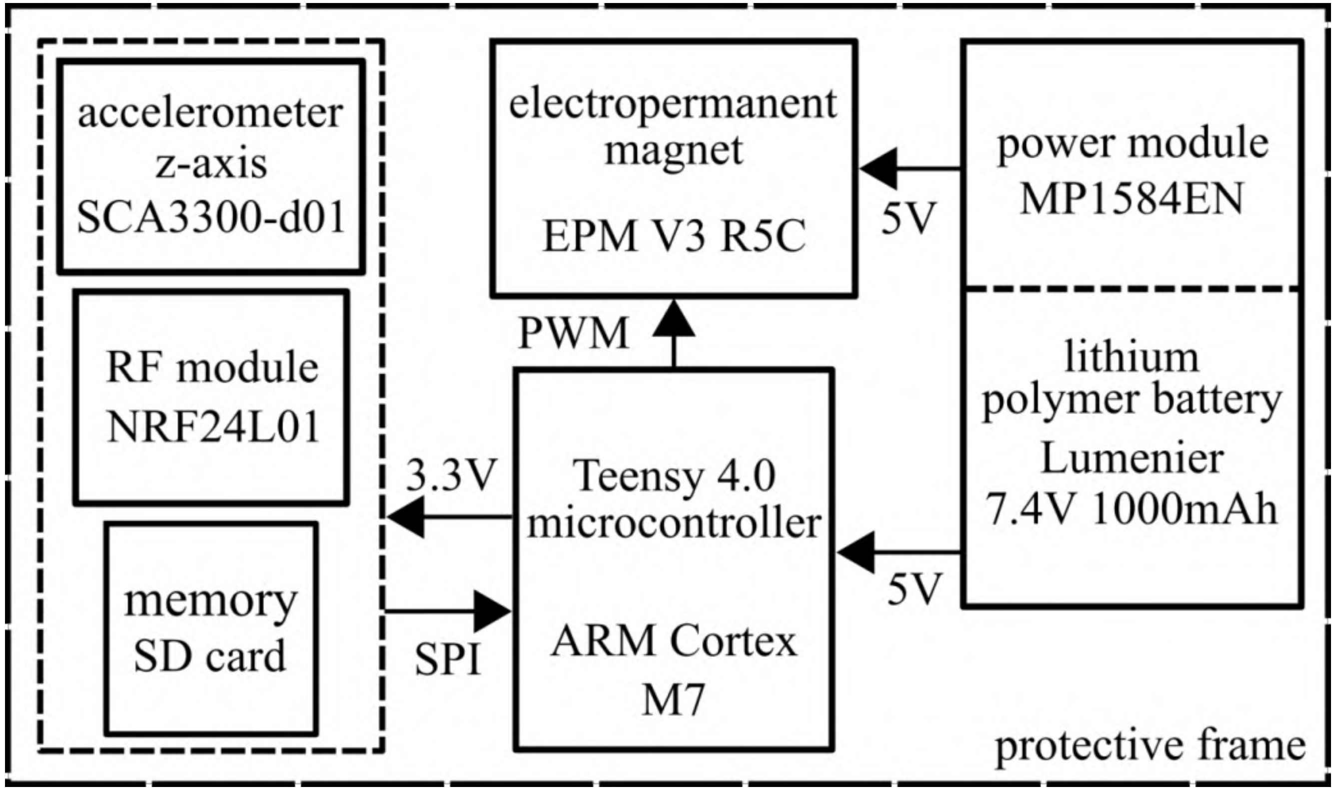






Sensor hardware and onboard systems

- Processor: ARM Cortex-M7 on Teensy 4.0 microcontroller.
- SCA3300-d01 MEMS accelerometer.
- EPM V3R5C electropermanent magnet.
- Nonvolatile memory (SD card) for long-term storage.
- Lithium polymer battery, voltage regulation and monitoring.
- NRF24L01 Nordic Semiconductor wireless transceiver.



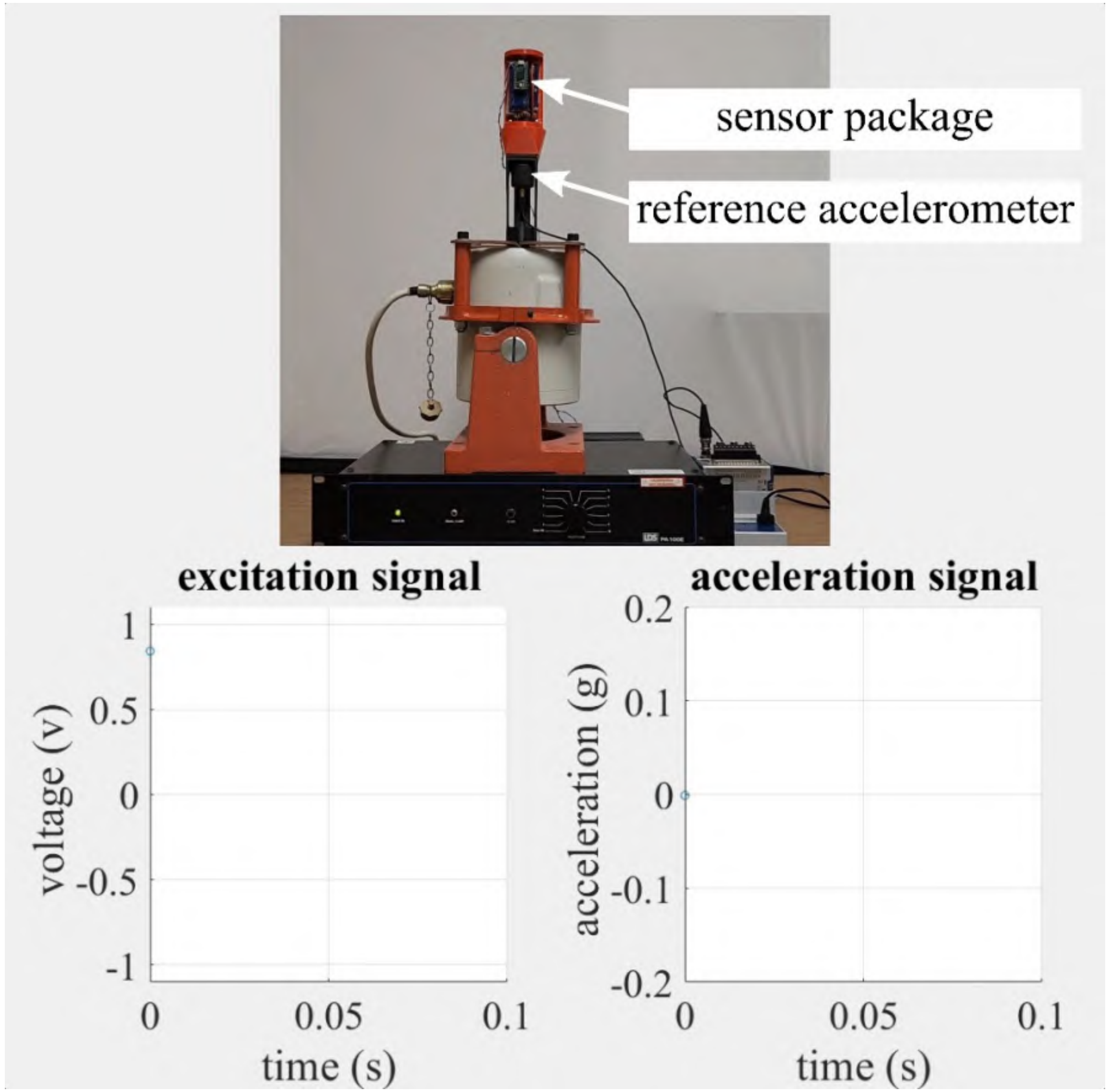
Signal conditioning and error compensation

- 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

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

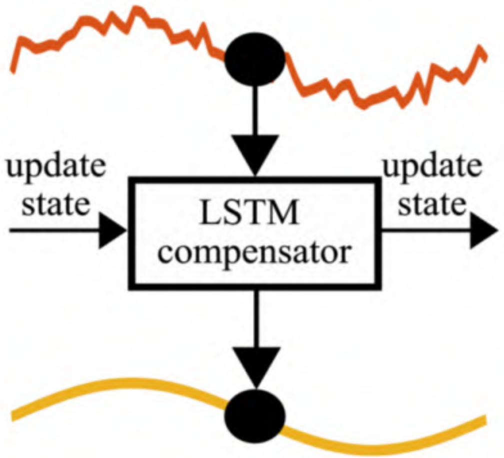
$$\text{SNR}_{\text{dB}} = 10\log_{10}\left(\frac{\sum_{i=1}^{\text{data length}}(\text{signal}(i))^2}{\sum_{i=1}^{\text{data length}}(\text{noise}(i))^2}\right)$$

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

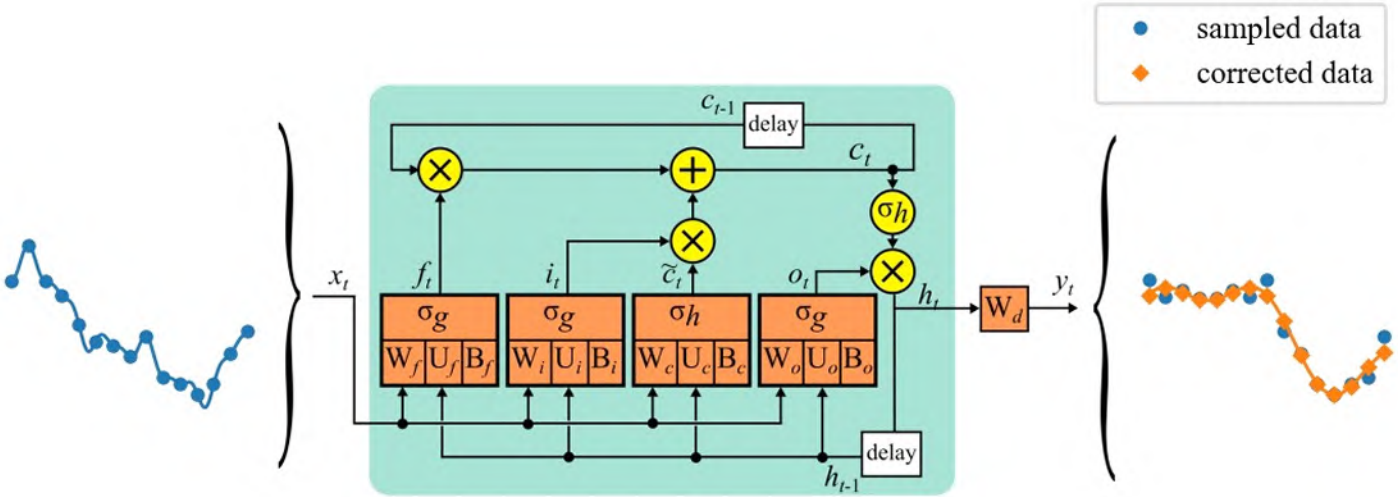


Signal conditioning

- 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)



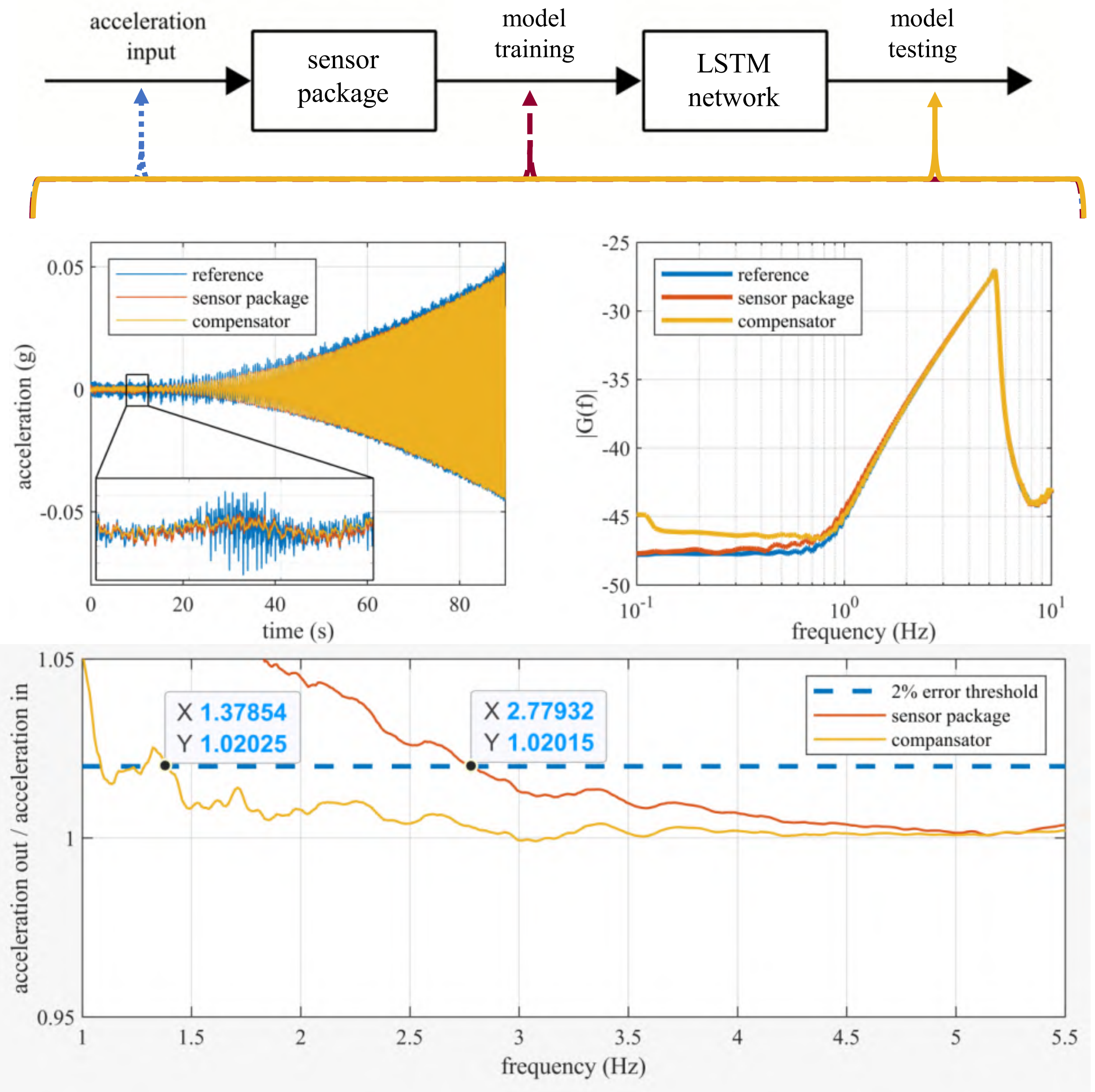
$$
\begin{aligned}
f_t &= \sigma(W_f x_t + U_f h_{t-1} + b_f) \\
i_t &= \sigma(W_i x_t + U_i h_{t-1} + b_i) \\
o_t &= \sigma(W_o x_t + U_o h_{t-1} + b_o) \\
\tilde{c}_t &= \tanh(W_c x_t + U_c h_{t-1} + b_c) \\
c_t &= f_t \circ c_{t-1} + i_t \circ \tilde{c}_t \\
h_t &= o_t \circ \tanh(c_t) \\
y_t &= W_d^T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



Signal error compensation

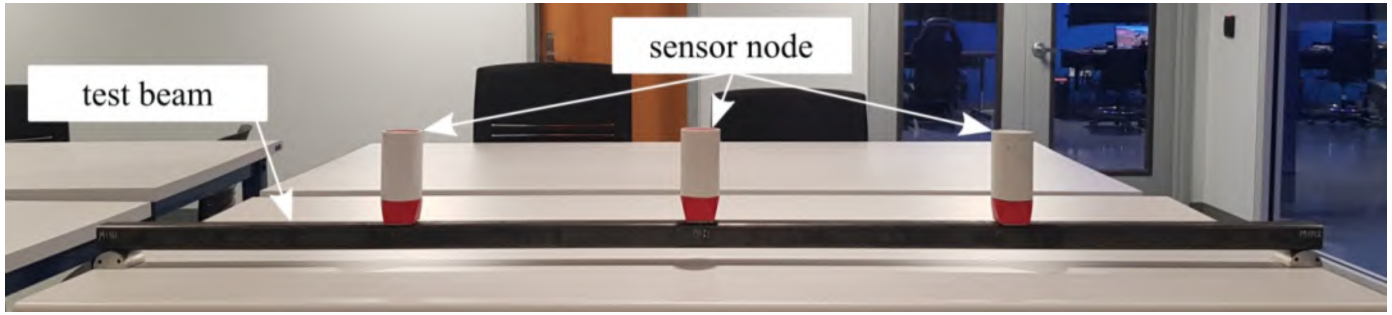
- LSTM compensator performance
  - For testing a chirp excitation in 0-5 Hz is used
  - SNR_{dB} enhancement of 9.34%
  - RMSE reduction of 19.66%
  - Usable bandwidth (< ±2%) is shown to increase form 2.78 Hz to 1.34 Hz
  - An overall increase in gain below 0.9 Hz due to training bias

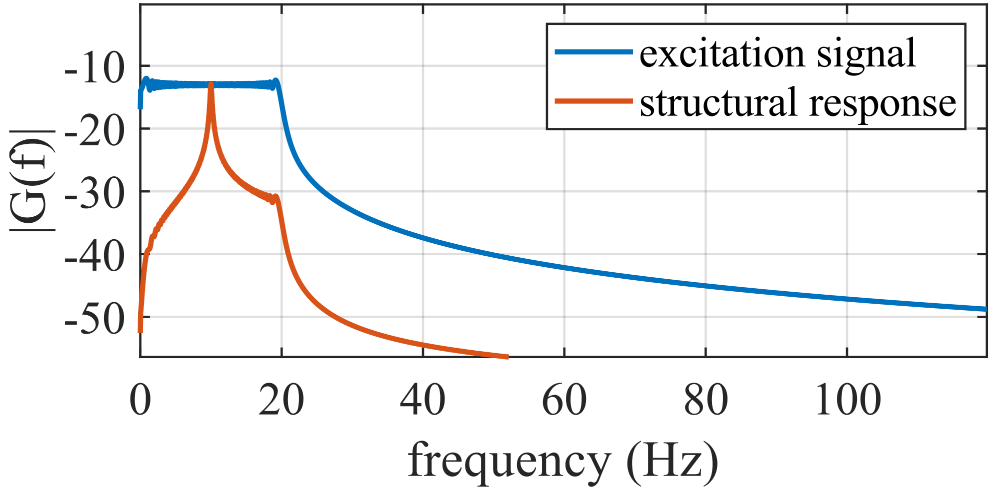
testing	$\mathrm{SNR}_{\mathrm{dB}}$	RMSE
sensor package	17.26 dB	1.795×10^{-3}
LSTM compensator	18.88 dB	1.442×10^{-3}
% improvement	9.34%	19.66%

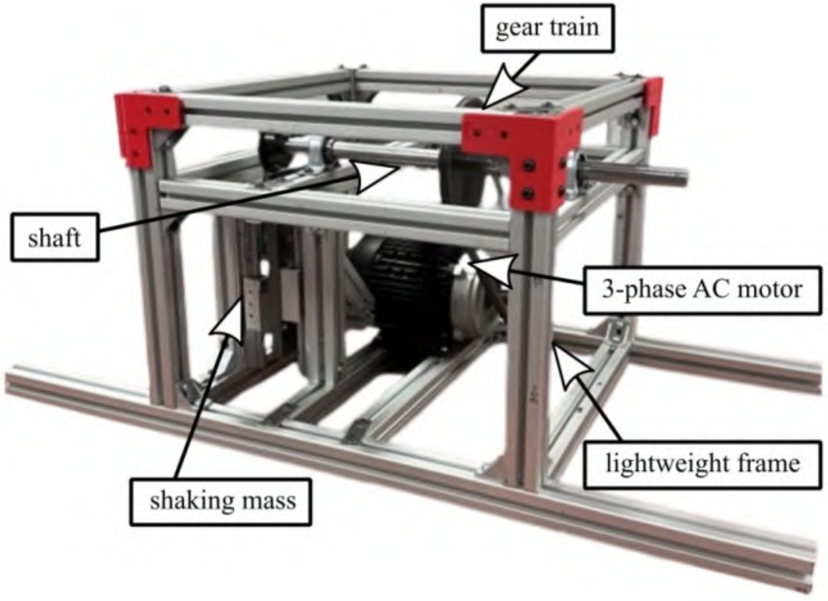


Sensing network for SHM

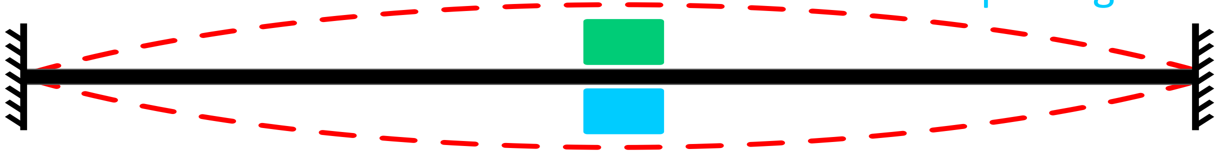
- sensors and actuators
- data acquisition and signal processing
- dynamic response and modal detection





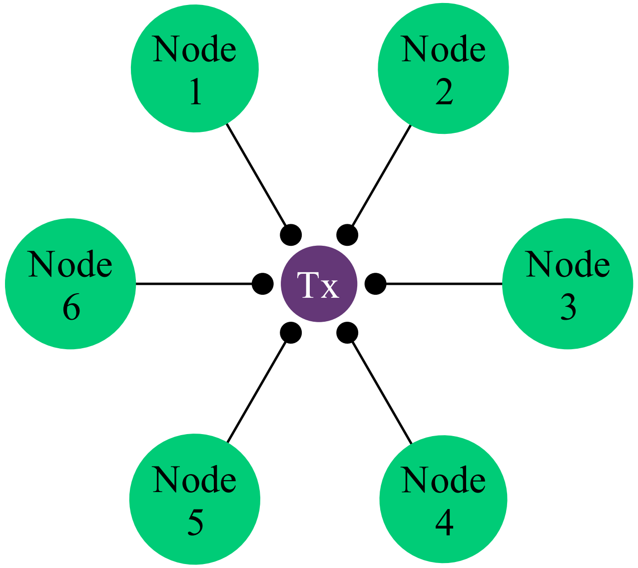


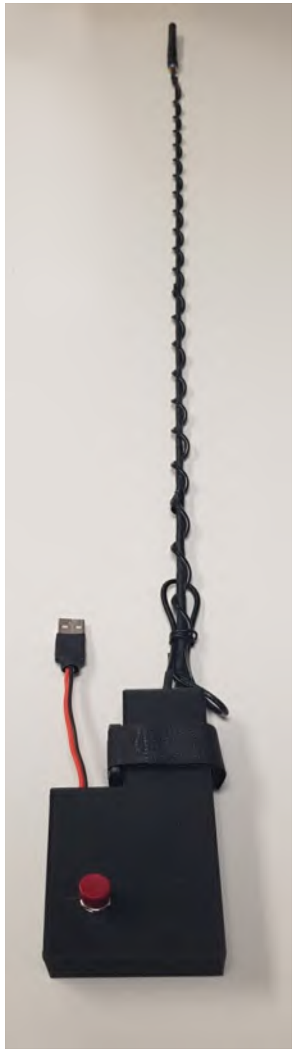
- 🟩 structural shaker
- 🟦 sensor package

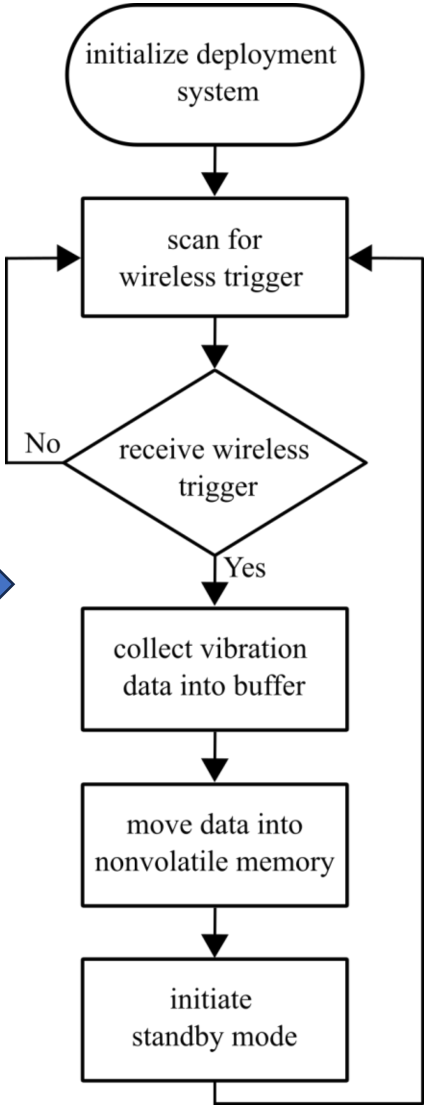


Sensing network for SHM

- Wireless system characteristics:
    - protocol: Enhanced ShockBust
    - bandwidth: 2.4 GHz
    - data rate: 2 Mbps
    - RF links: 6 channels







initialize deployment system

scan for wireless trigger

receive wireless trigger

No

Yes

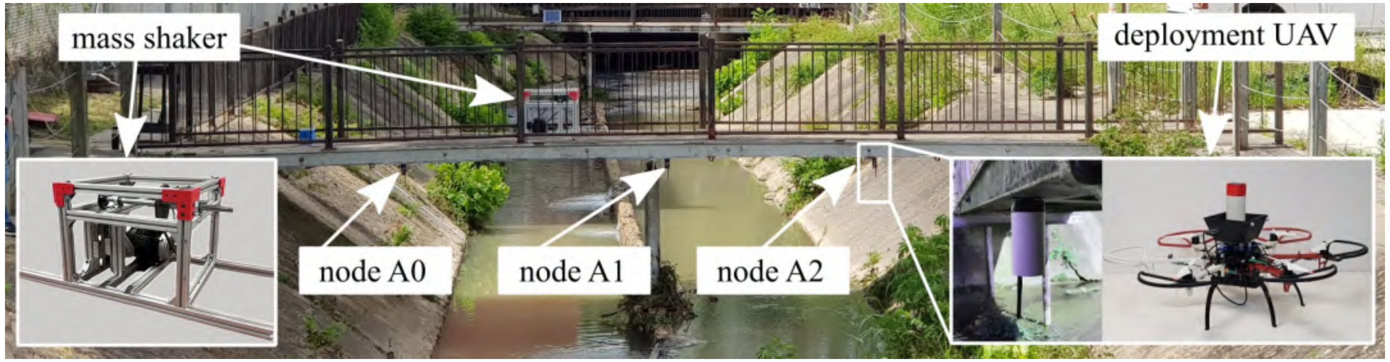
collect vibration data into buffer

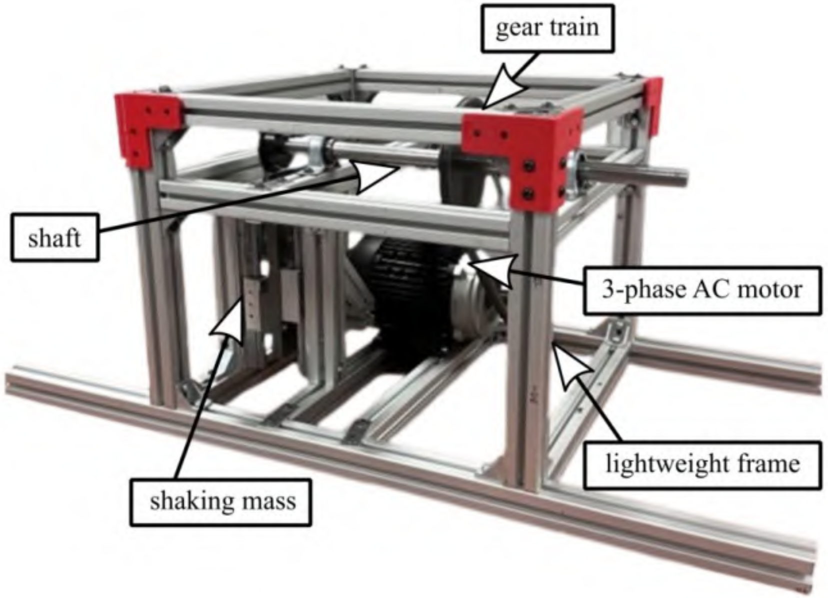
move data into nonvolatile memory

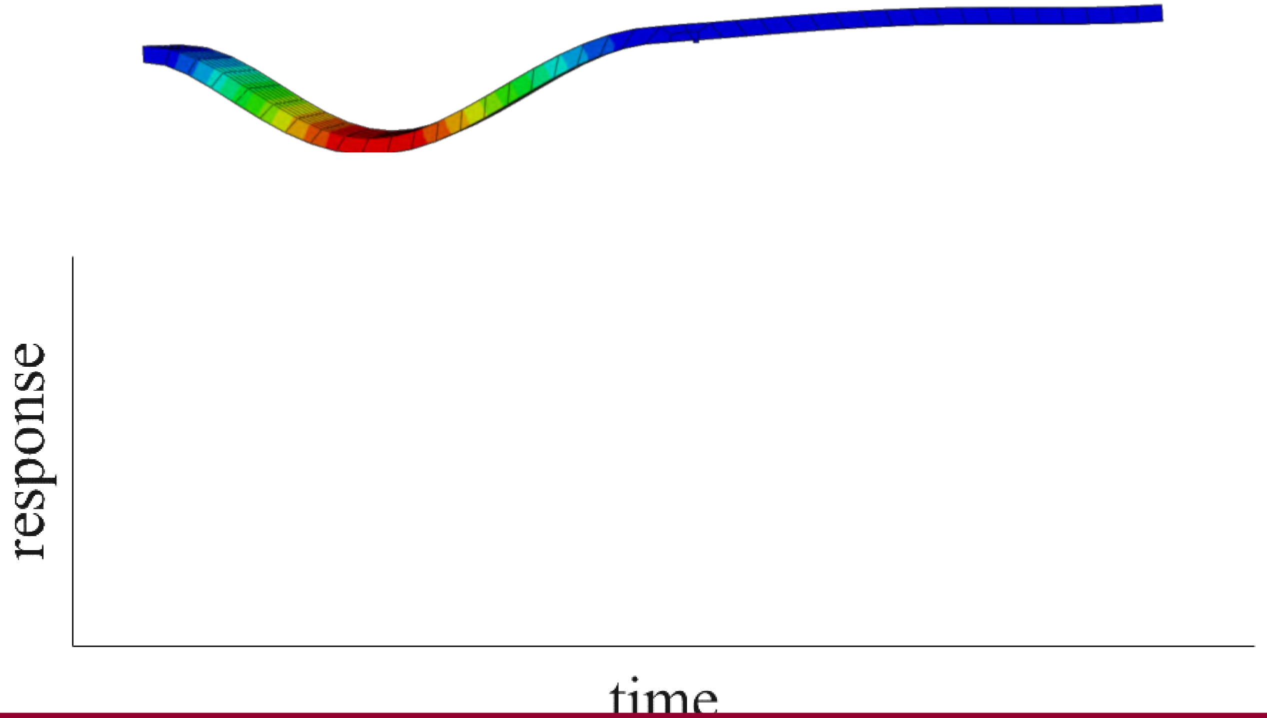
initiate standby mode

Case study for using UAV-deployable wireless sensor network for mode detection

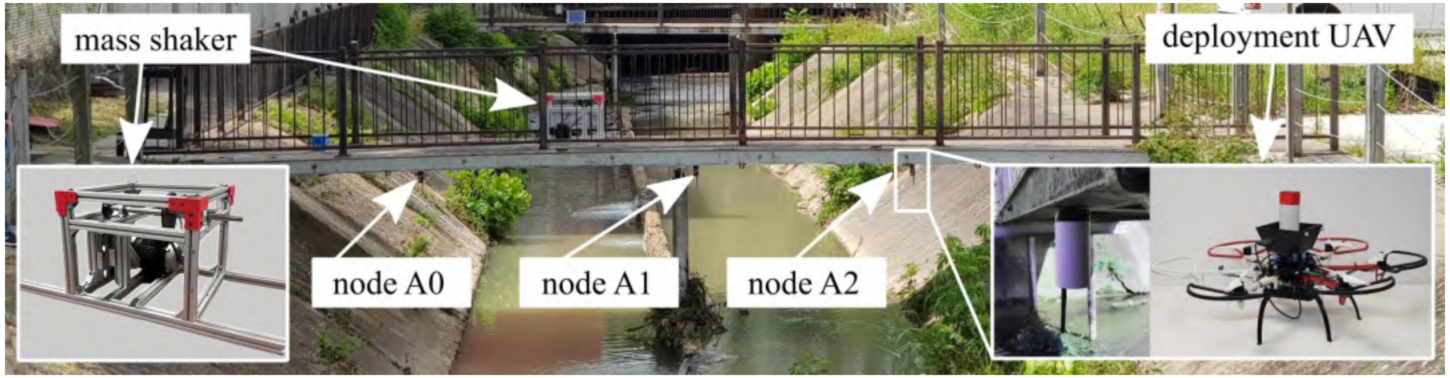
- Active modal detection using UAV-deployable sensing network
- data acquisition and real-time synchronization
- signal processing and state estimation

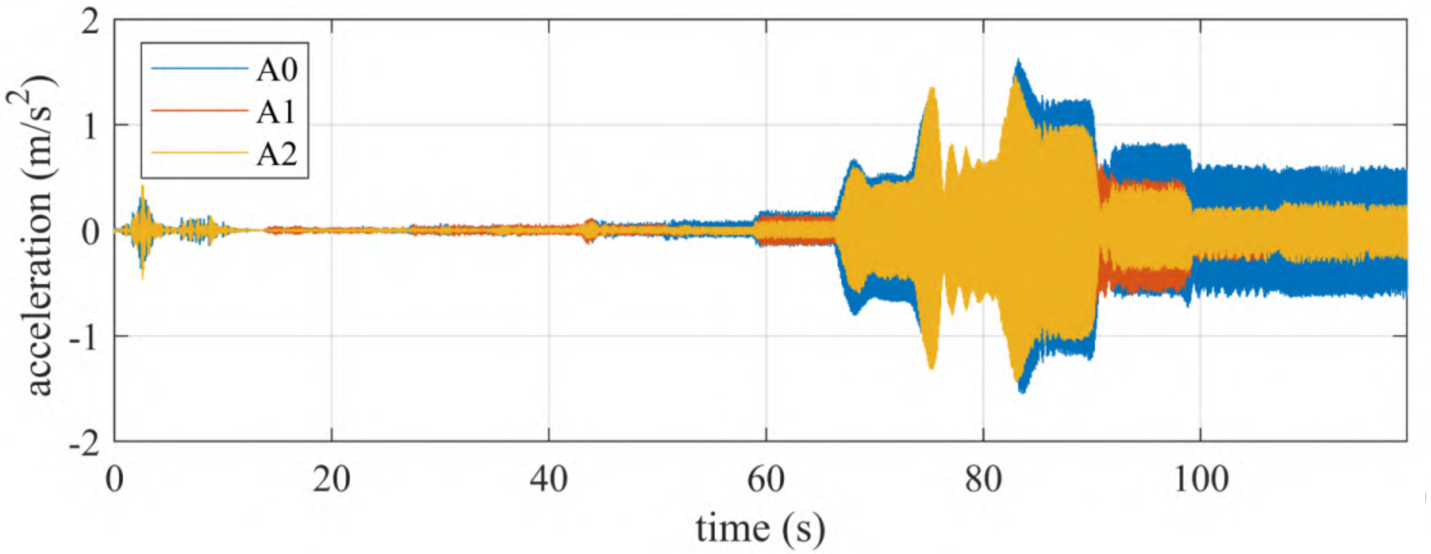




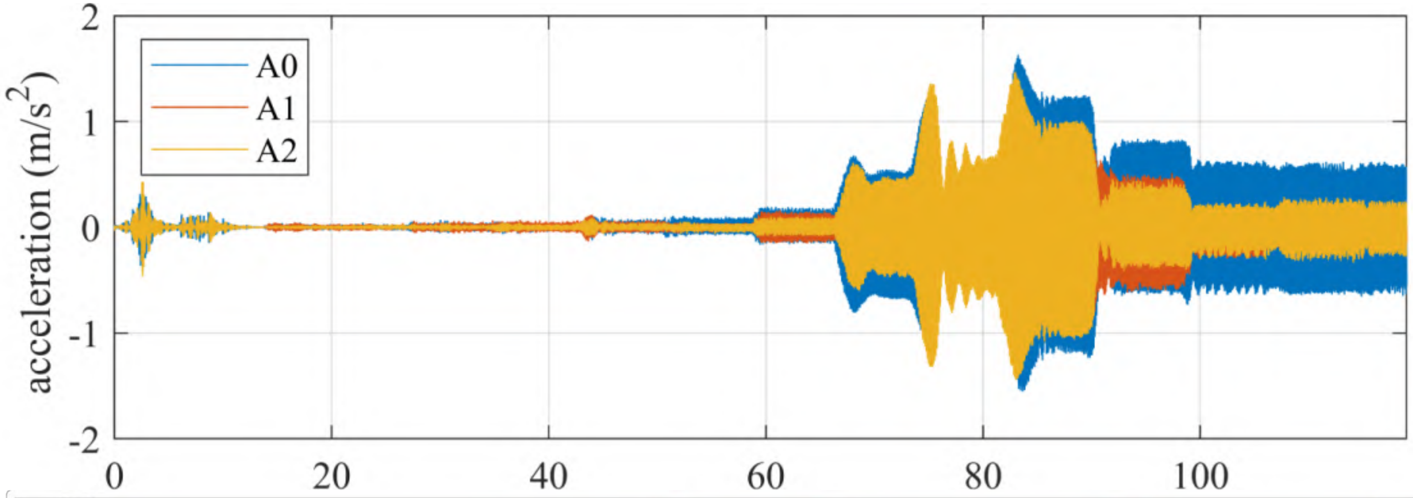


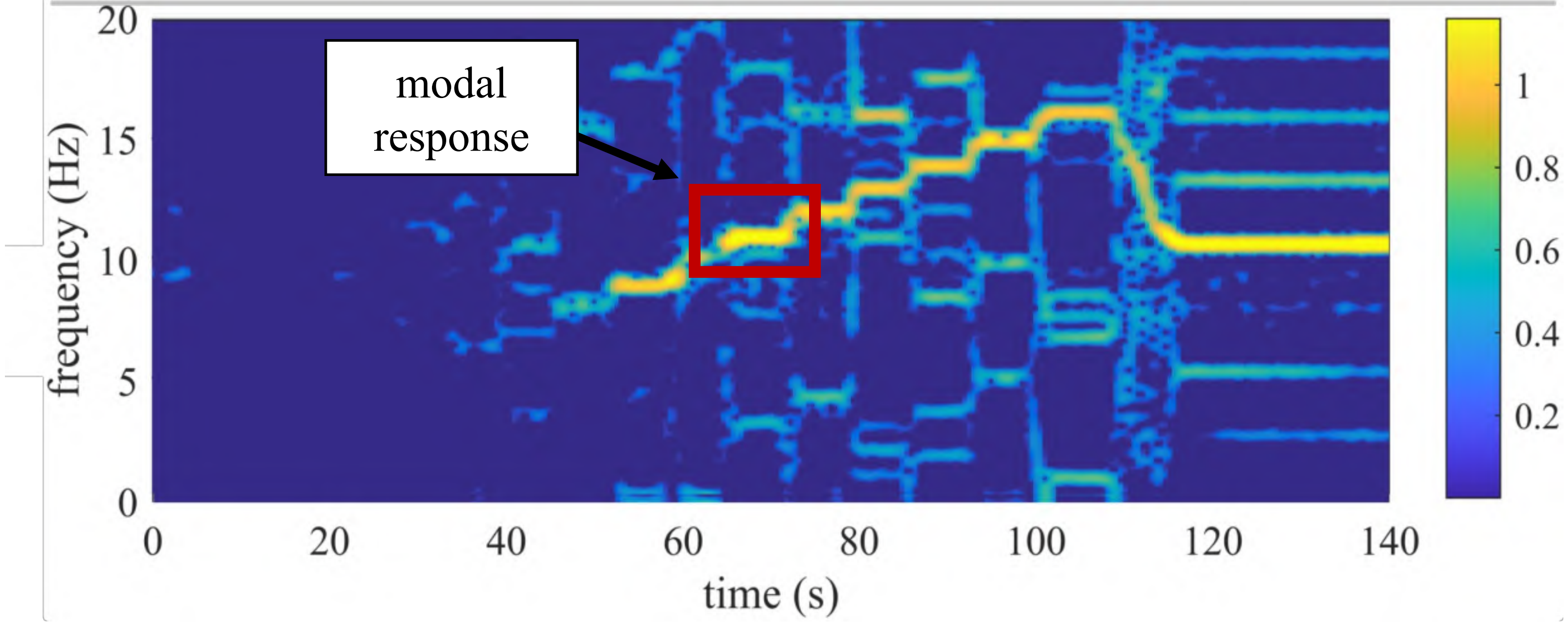
Time and frequency response of a pedestrian bridge





Time and frequency response of a pedestrian bridge

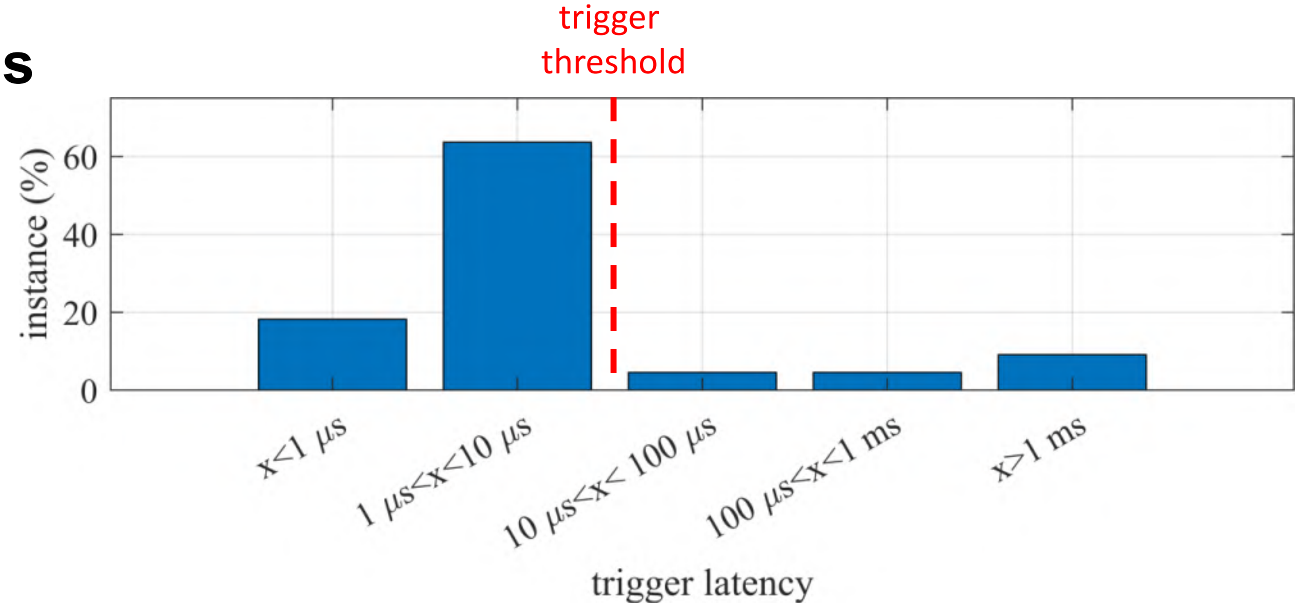


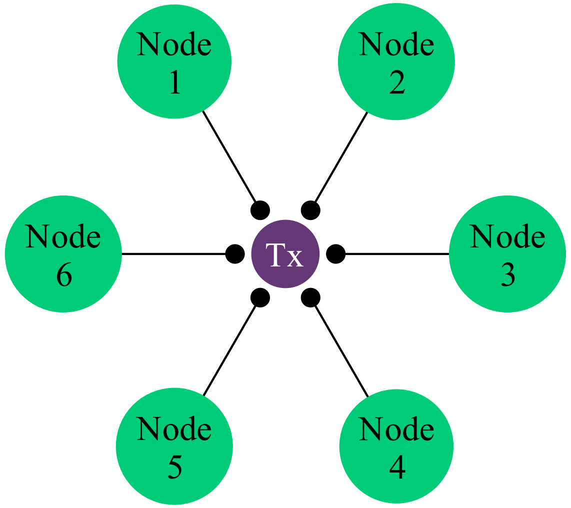


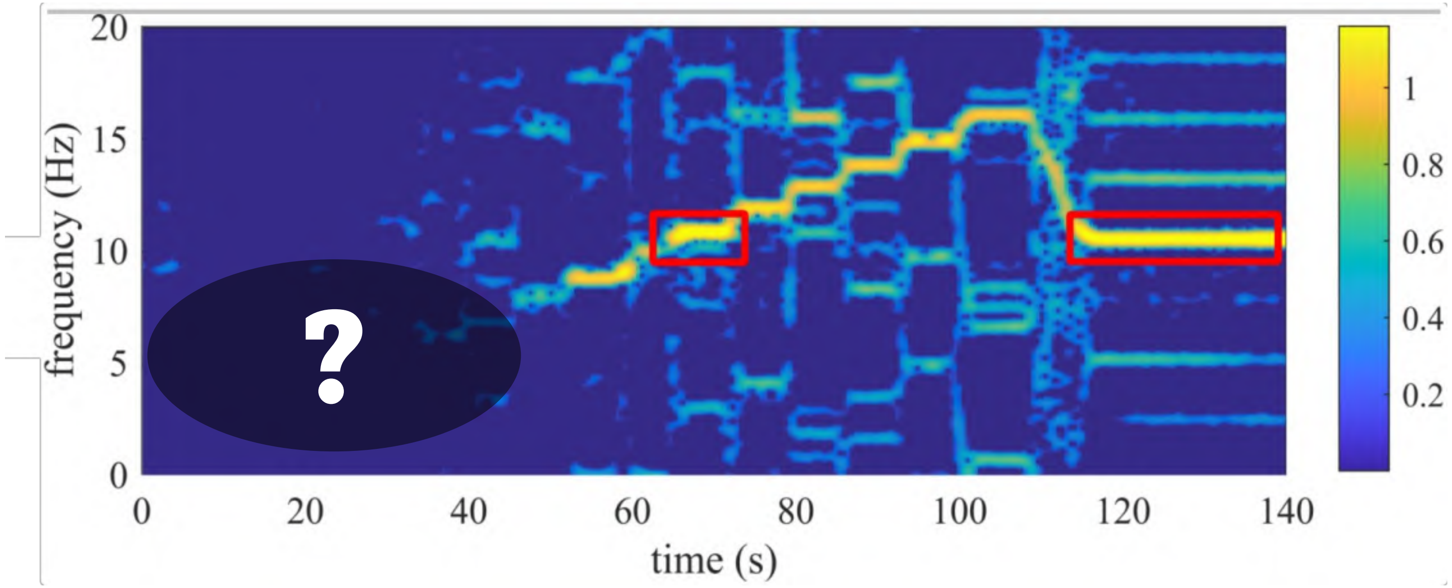
modal response

Sensing system experimental challenges

- wireless trigger time latency (~85% < 10 μs)
- low-magnitude low-frequency response detection

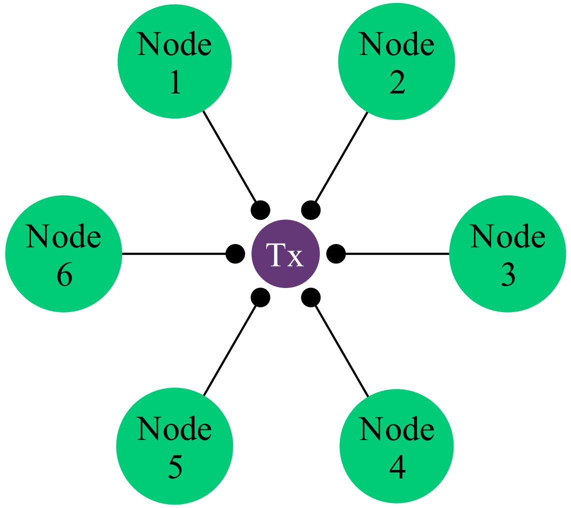


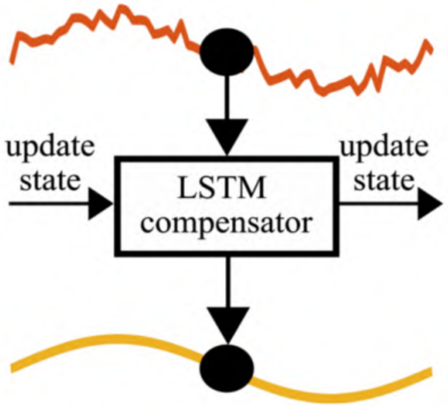


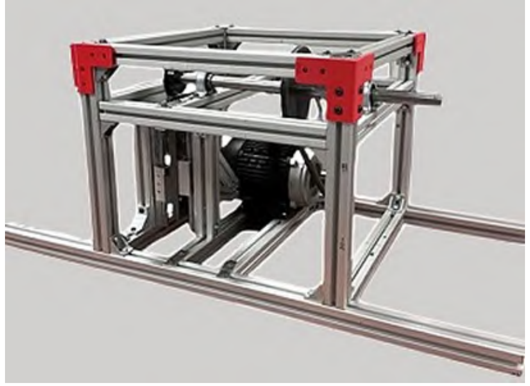


System overview

- deployment and retrieval system
- sensor hardware and onboard systems
- signal conditioning and error compensation
- wireless sensing network

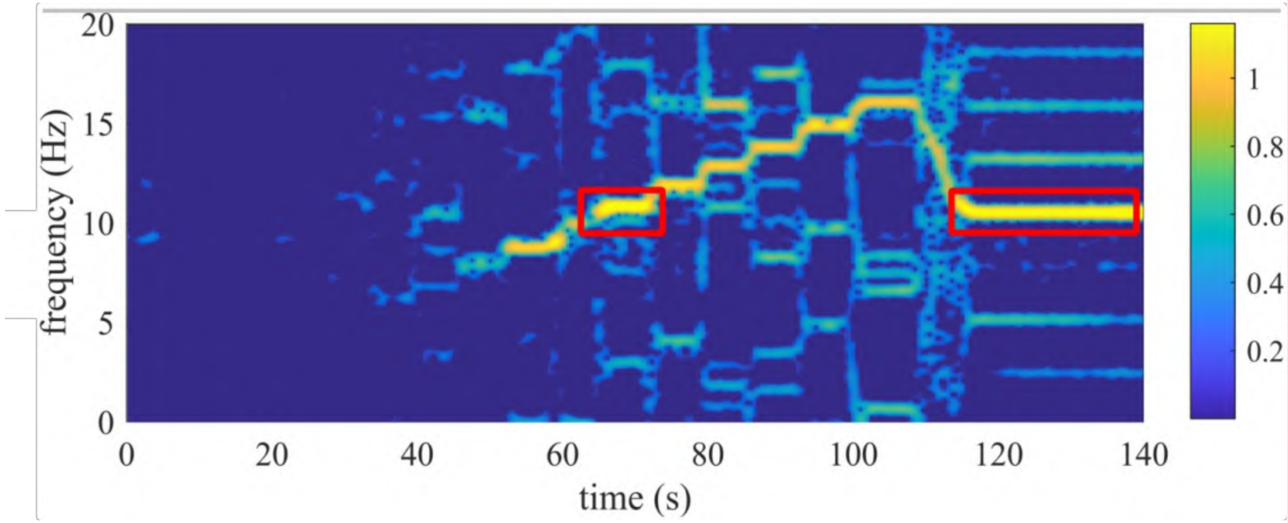


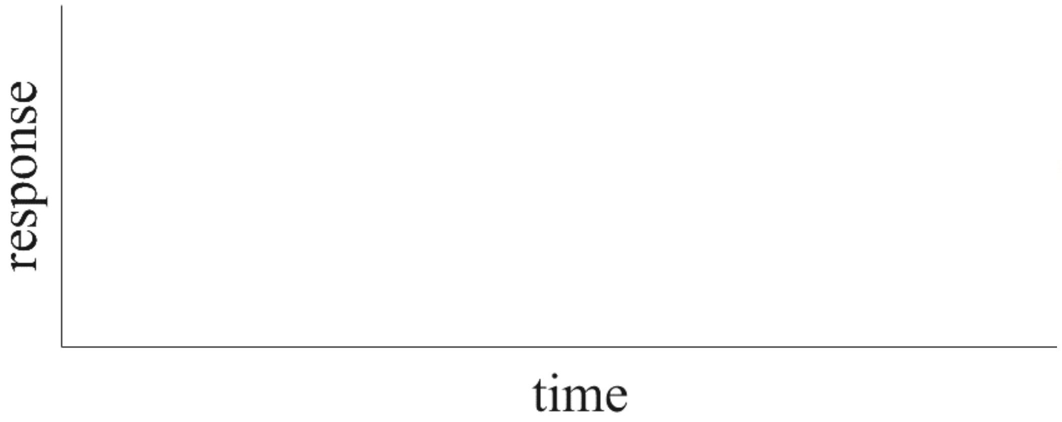


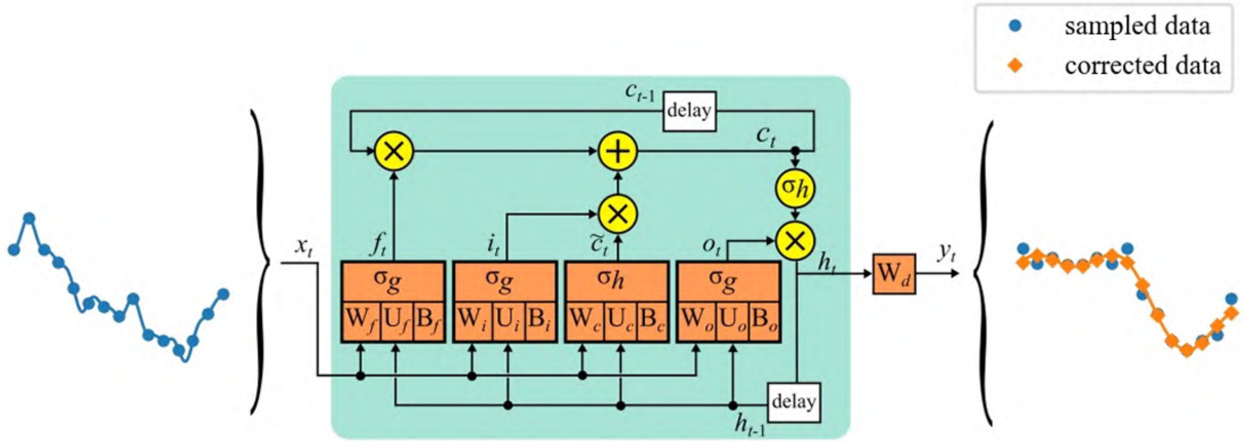


Future work:

- edge computing implementation
- autonomous UAV delivery







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 1937535, 1956071, 2152896, and 2237696.

Thank you

Questions?

Author Information
Name: Austin R.J. Downey
Email: austindowney@sc.edu