UAV-Based Sensor Deployment and Edge Computing for Rapid Infrastructure Assessment

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The ARTS-Lab at USC

We use

foundational science

Day School

to develop essential tools

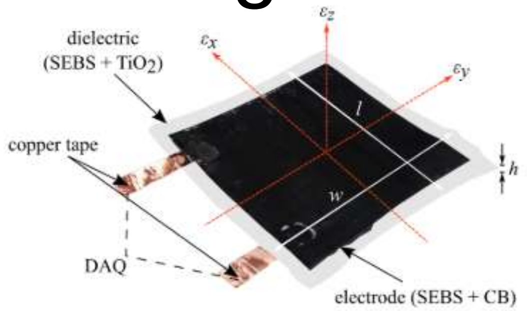
Dan Thompson

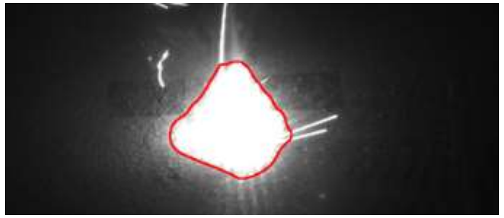
to solve real-world problems

public domain

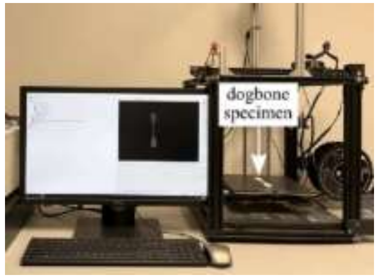
We are Engineers (mostly)

Sensing

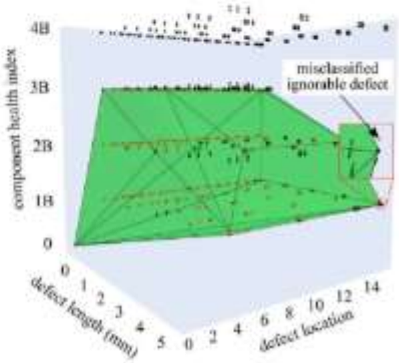


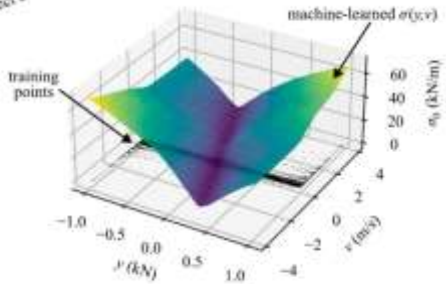


Data Assimilation

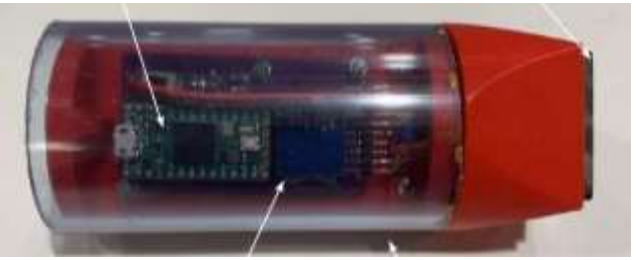


AI/ML

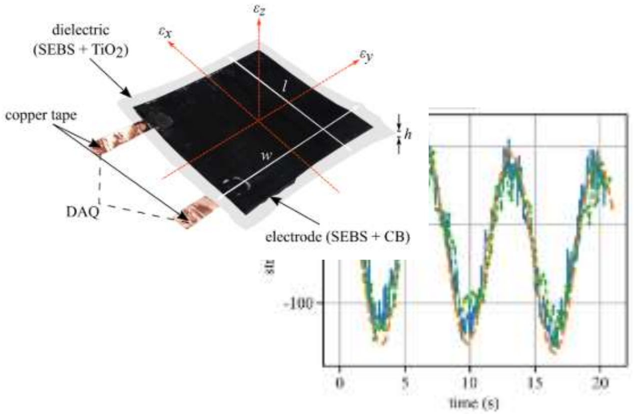




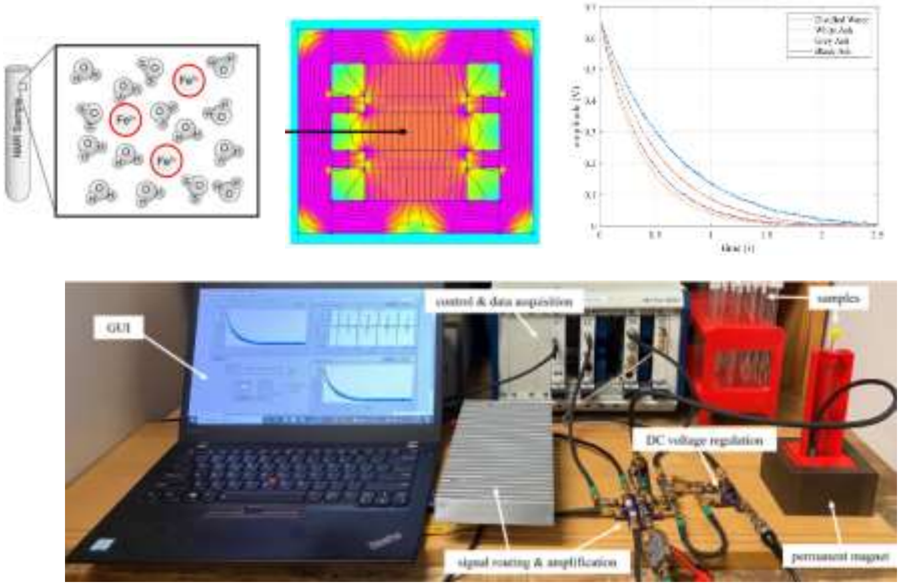
Embedded Systems



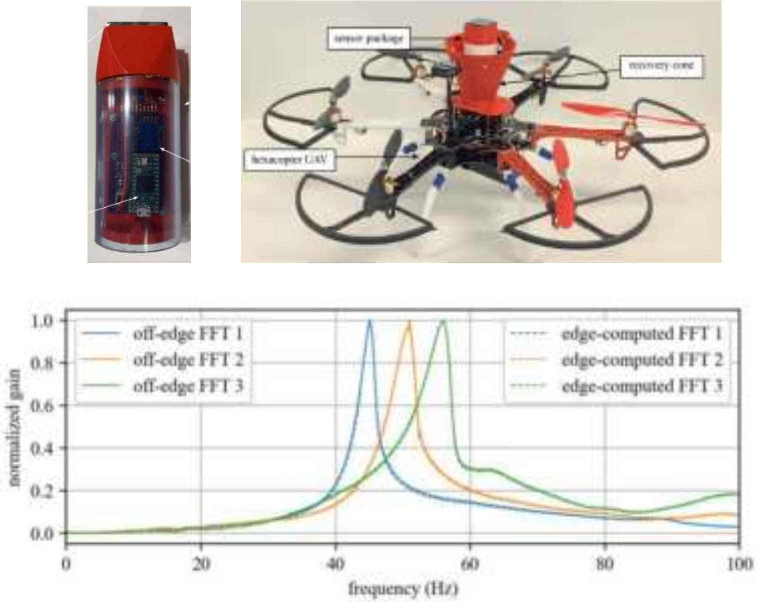
Sensing



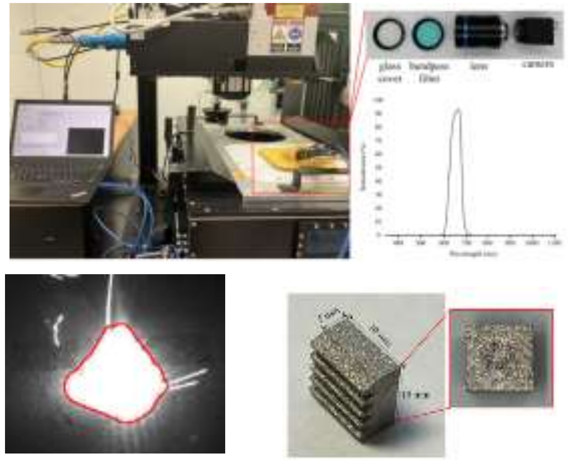
Flexible Electronics



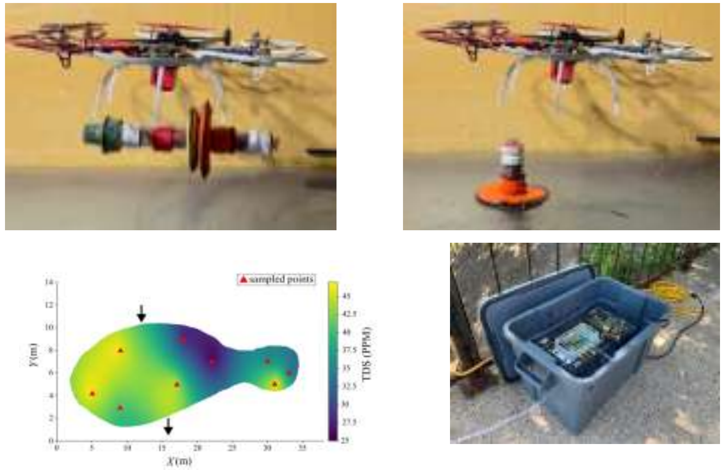
Nuclear Magnetic Resonance



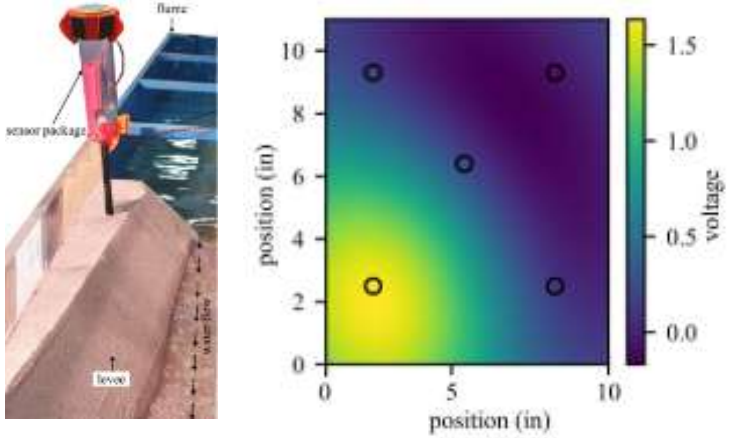
Vibration Sensors



In Situ Monitoring of AM

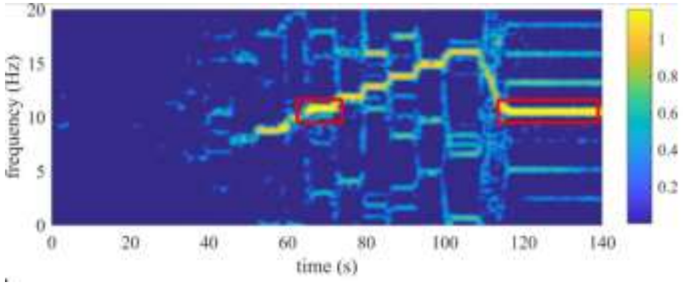


Water Quality Sensors

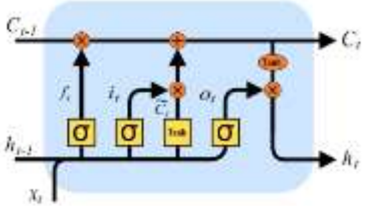


Geo Technical Sensors

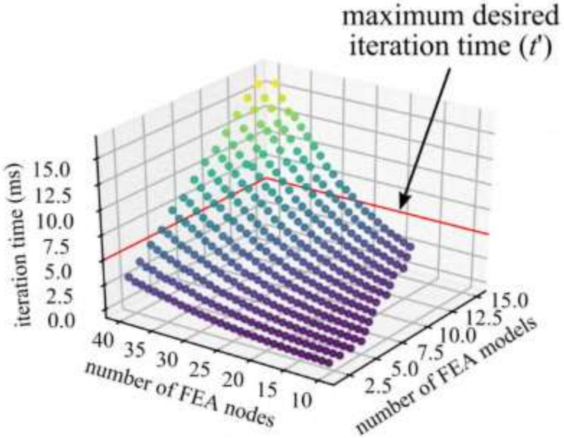
Data Assimilation



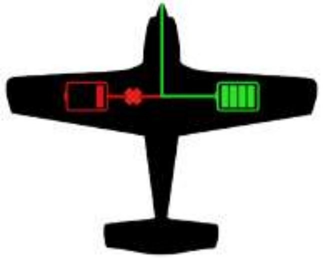
Civil Structures

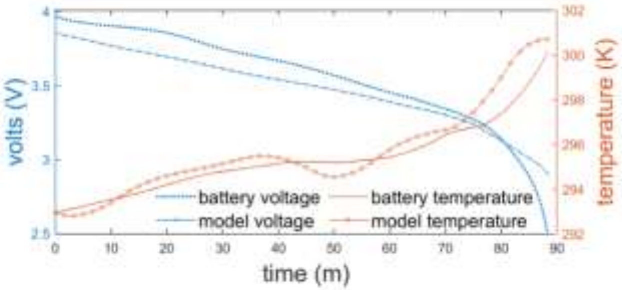


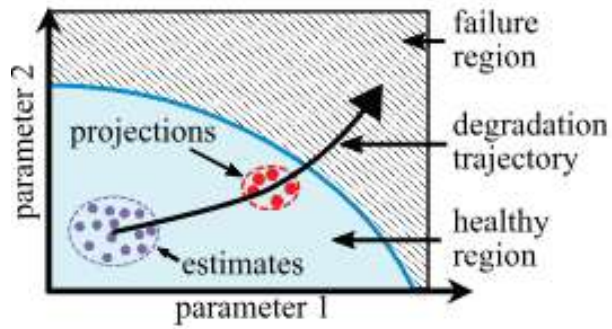
$$\frac{-1}{\alpha} = \sum_{r=1}^{m} \frac{v_r^2}{\omega_r^2 - \Omega_r^2}$$



High-Rate Systems

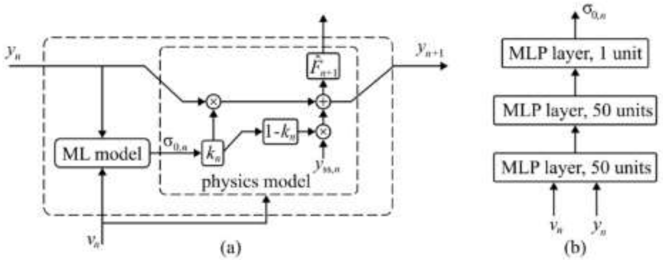


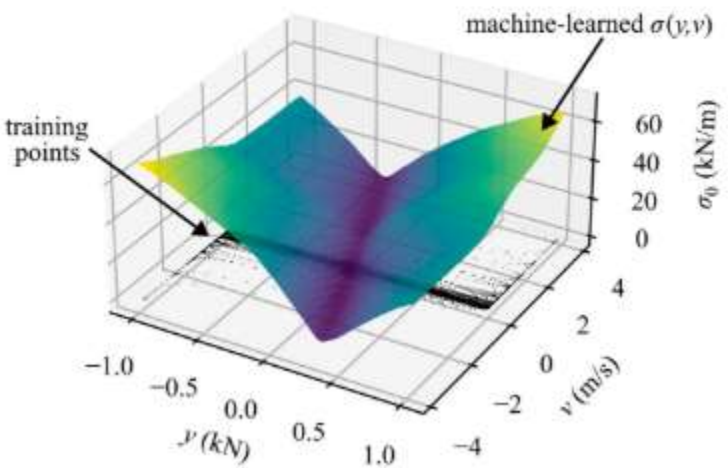




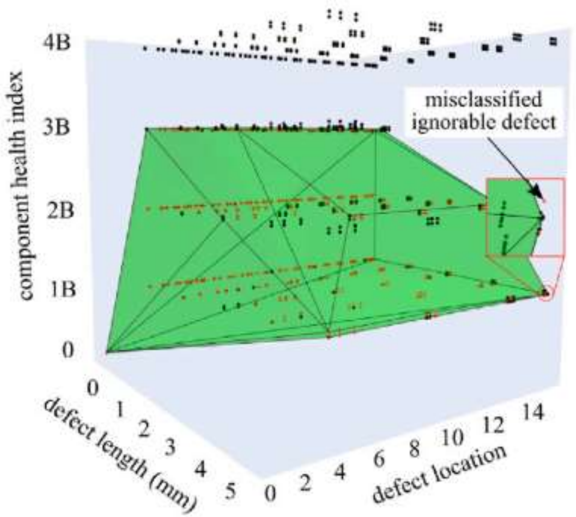
Battery Systems

AI/ML

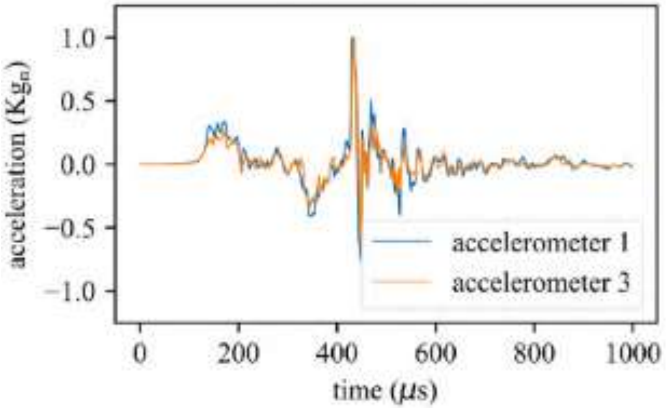




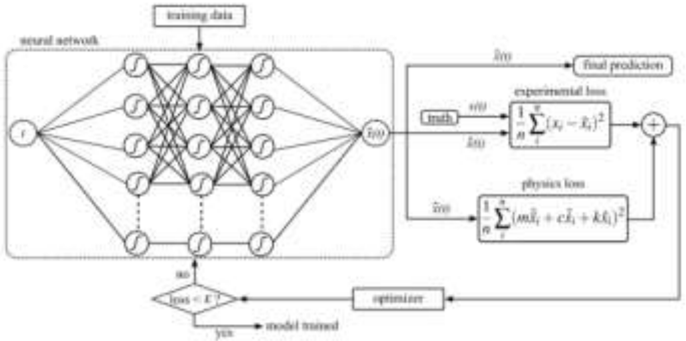
Explainability

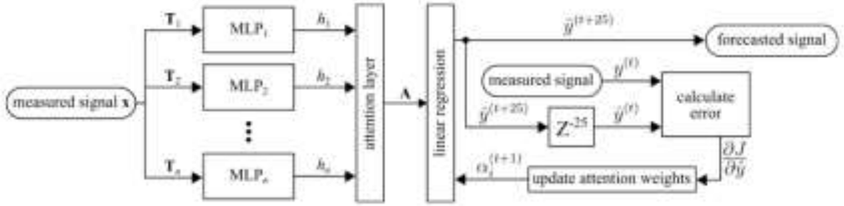


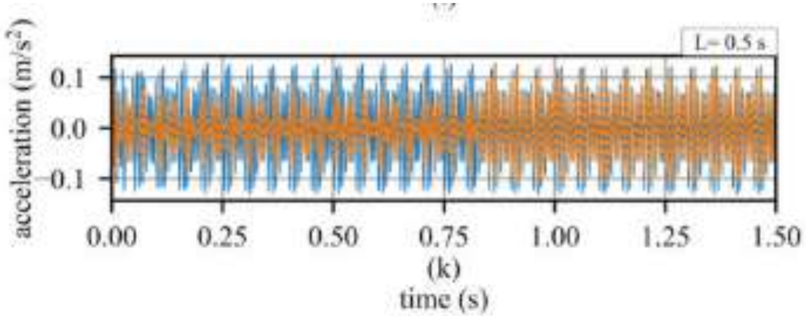
Decision-making



Generative

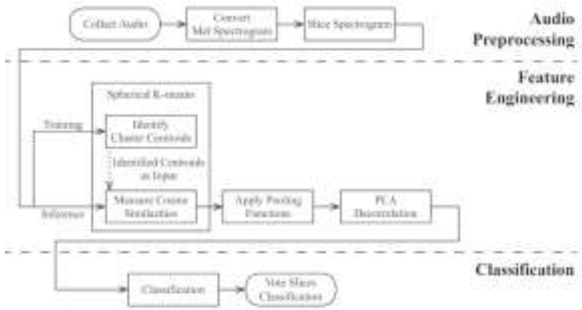




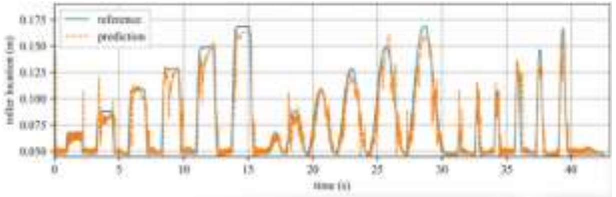


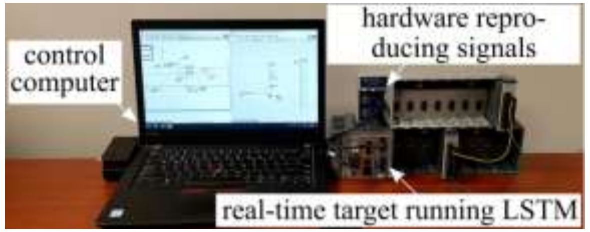
Forecasting

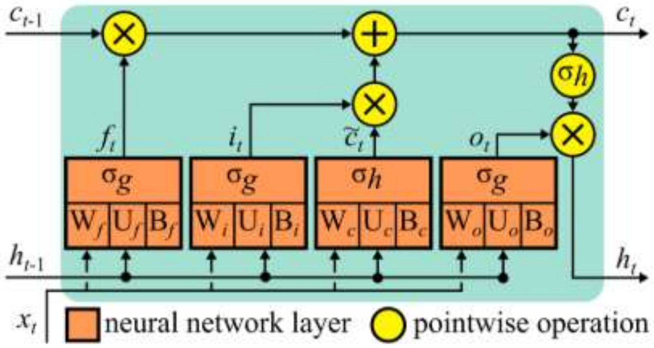
Embedded Systems



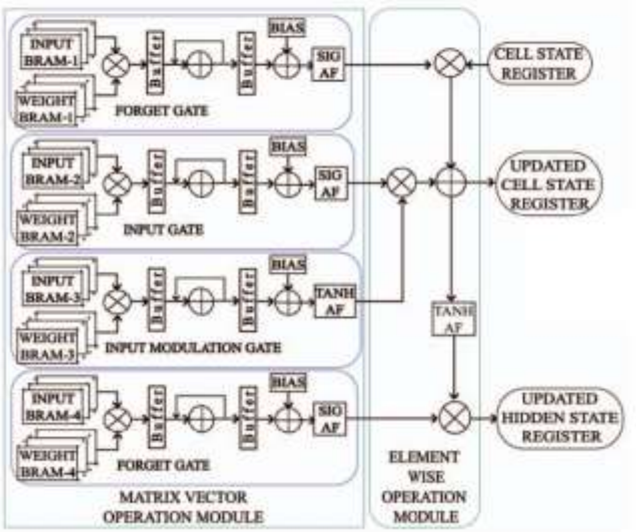
Microcontroller/ microprocessor

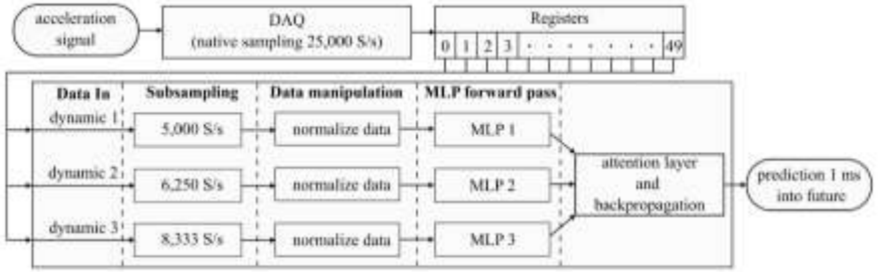






Real-Time OS

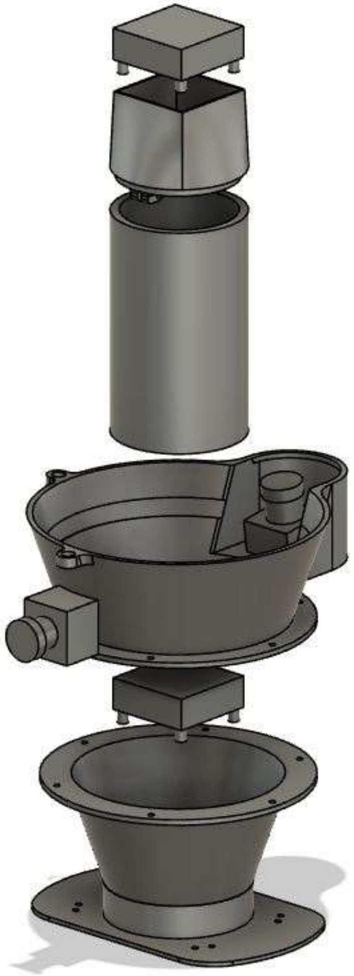


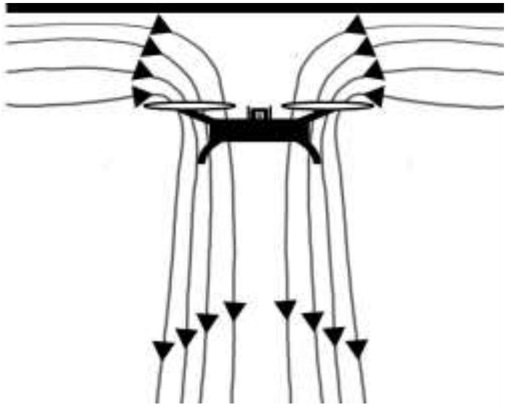


FPGA

Outline for Today's Talk:

1. Driving Challenges in UAV-deployed Sensors
2. UAV and Sensor Hardware
3. Edge Processing of Sensor Signal
4. Networks of UAV-deployed Sensors
5. Future Directions and Preliminary Results
6. Conclusion





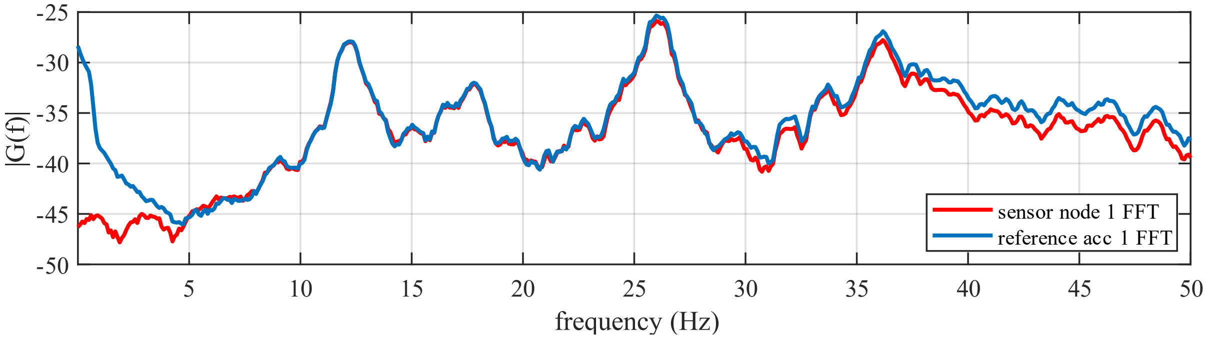
Driving Challenges in UAV-deployed Sensors

Challenges and Innovations in Structural Health Monitoring

- **Current Limitations:** Traditional SHM relies on specialized equipment and skilled personnel, limiting speed and flexibility.
- **Deployment Challenges:** Remote, hazardous locations, or decaying structures add time, cost, and safety risks to manual sensor deployment.
- **Need for Rapid SHM Solutions**: Real-time, data-driven insights, autonomous sensor deployment, and effective wireless communication are critical for safe, efficient monitoring.

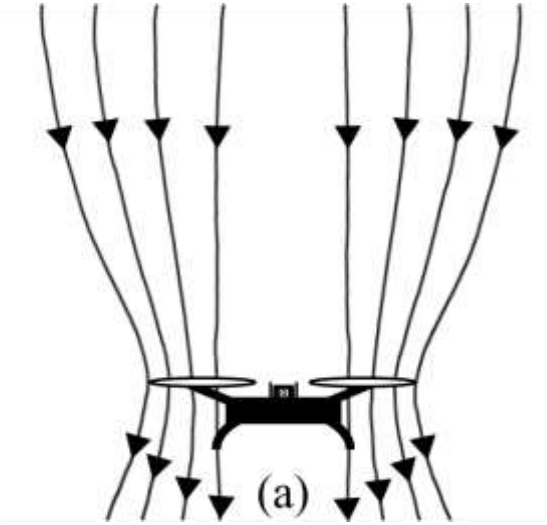
Our Solution – UAV-Deployable Sensor Package

- **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

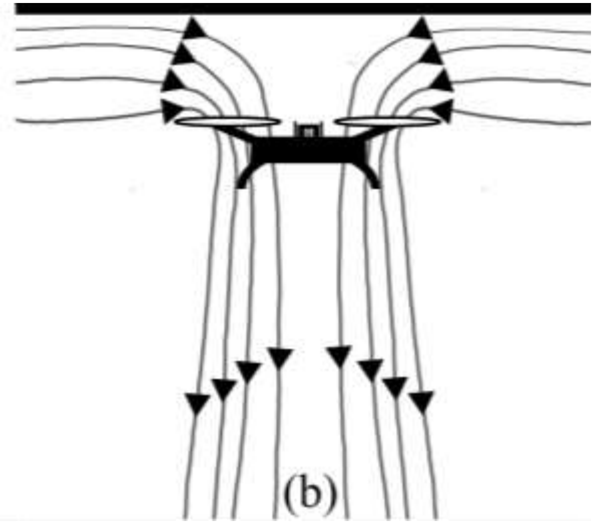


Understanding the Ceiling Effect in UAVs

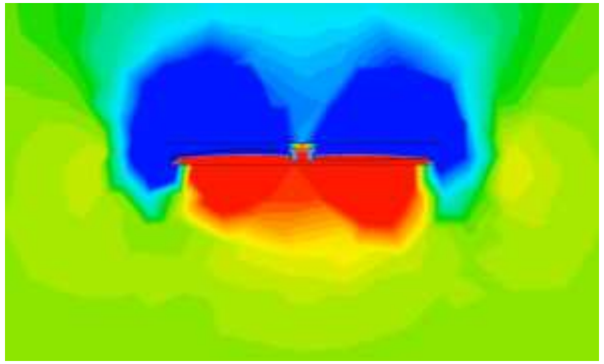
- **Definition:** The ceiling effect occurs when a propeller operates near a barrier, like a ceiling, altering the airflow and making lift more efficient.
- **Cause:** Impeded airflow above the propeller leads to a pressure drop, creating an increase in lift.
- **Impact on Control:** The UAV operator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

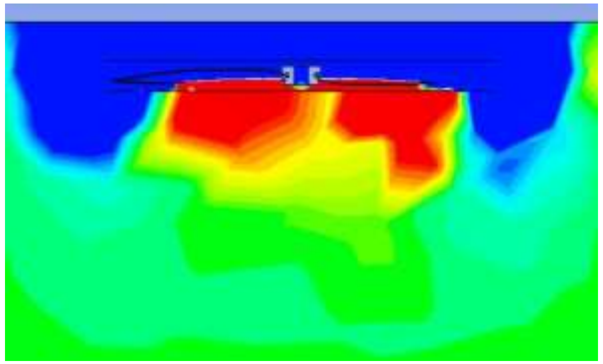


propeller in open air



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

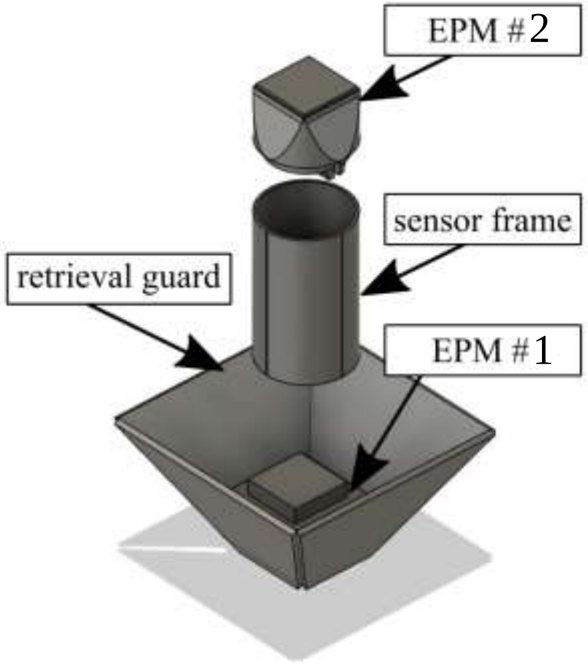
No researchers were harmed during this endeavor!

UAV and Sensor Hardware

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

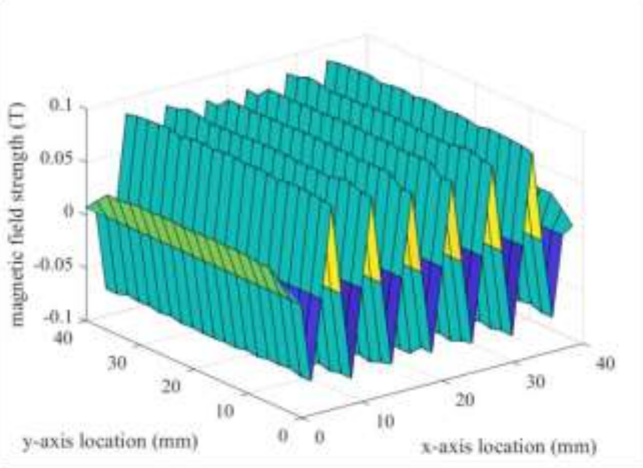
Deployment and Retrieval System

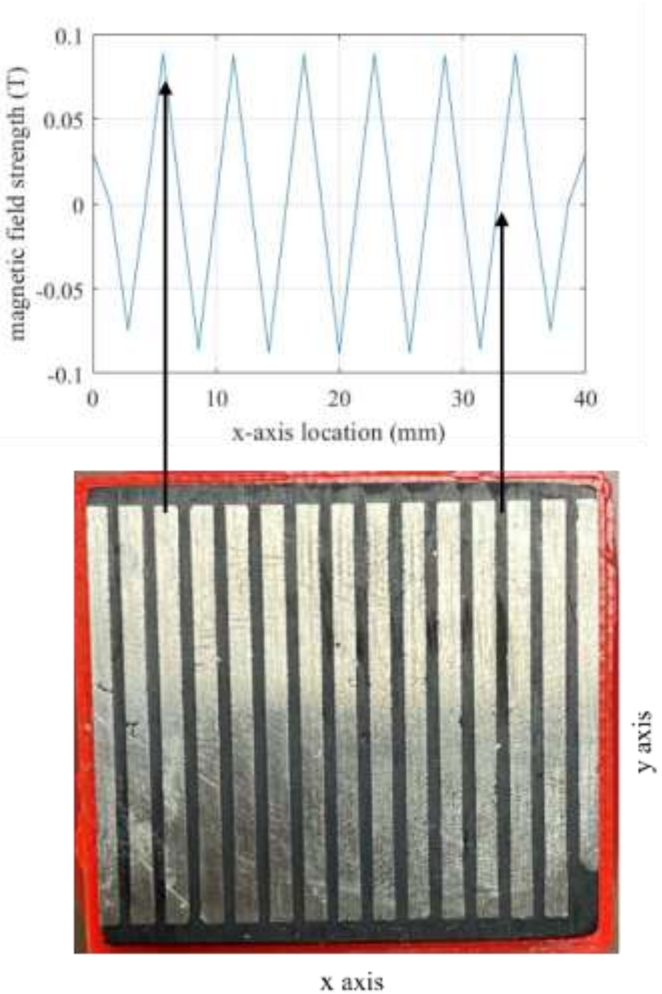


	EMP #1	EPM #2
Deployment	On	Off
Retrieval	Off	On

Deployment and retrieval system

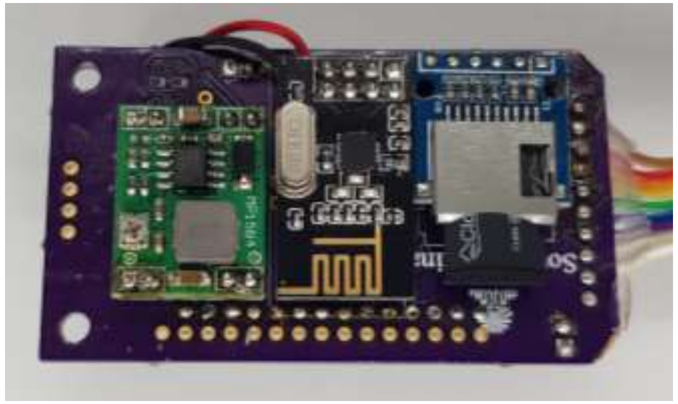
- **Electromagnetic Activation:** Pulse-activated magnetic polarity control
- **Energy-Efficient:** Holds magnetic state without continuous power
- **Versatile Applications:** Ideal for clamping, lifting, and sensor deployment
- **Stable Magnetic Configuration:** Maintains position securely using South-South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

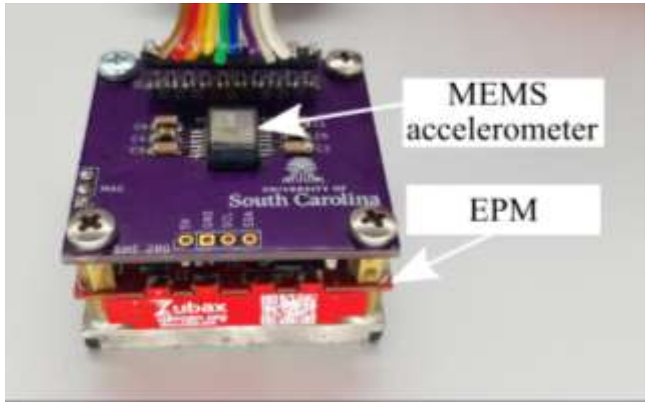


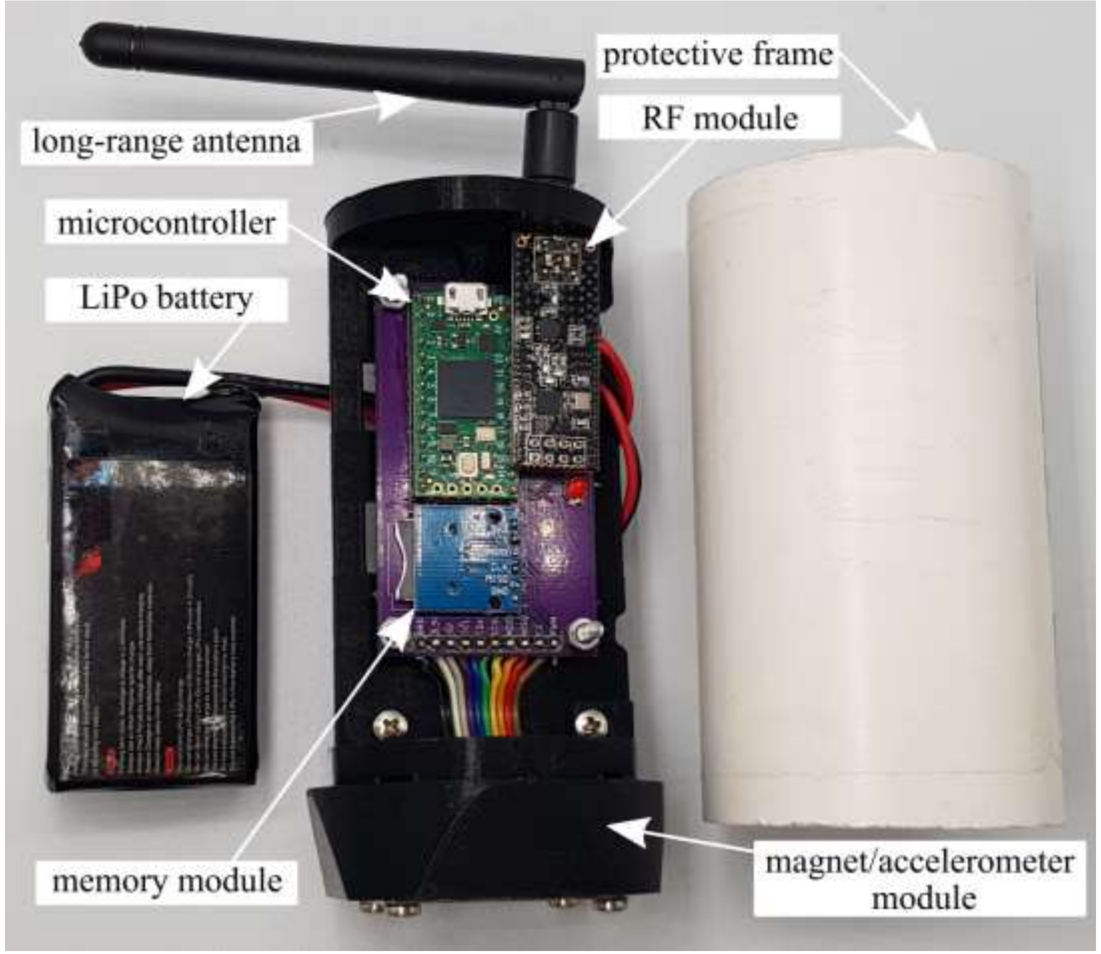


Sensor hardware and onboard systems

- **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

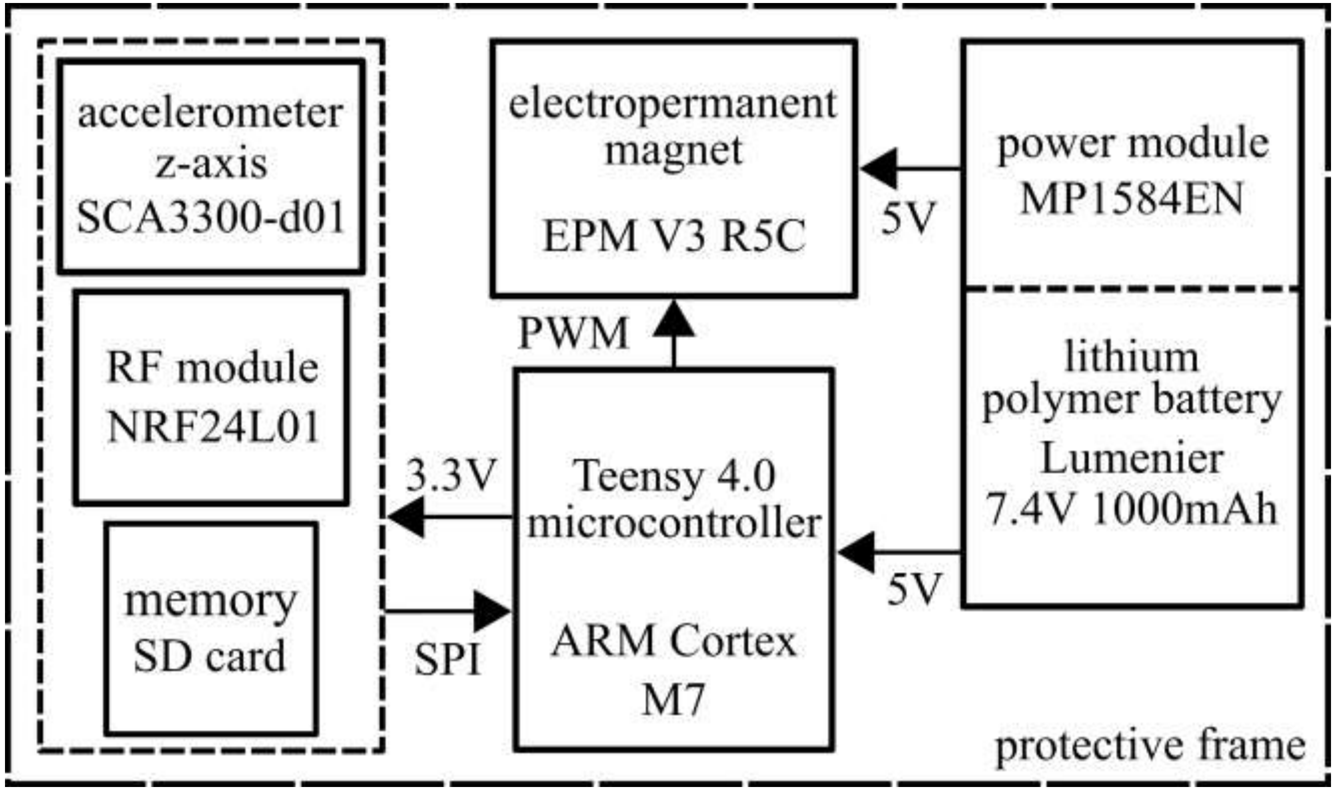






Sensor Package System Architecture

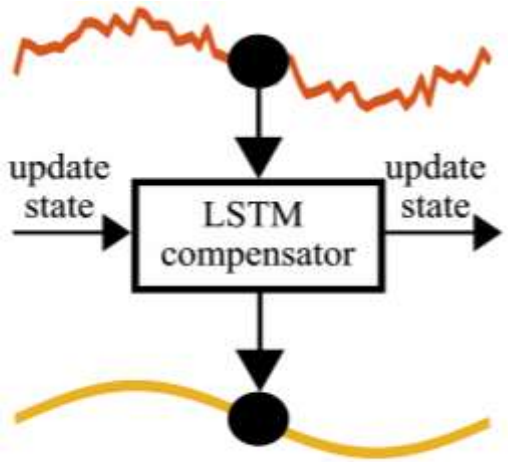
- **Core Processing:** Teensy 4.0 microcontroller (ARM Cortex M7) with SD card for data storage
- **Communication:** High-sensitivity accelerometer and RF module for real-time data and commands



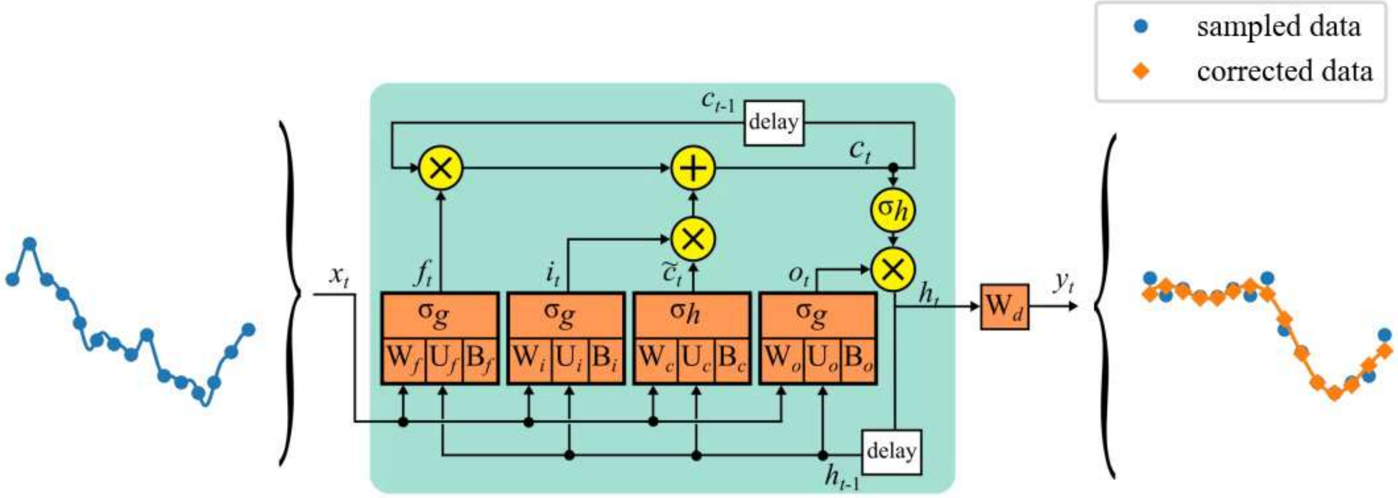
Edge Processing of Sensor Signal

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)



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



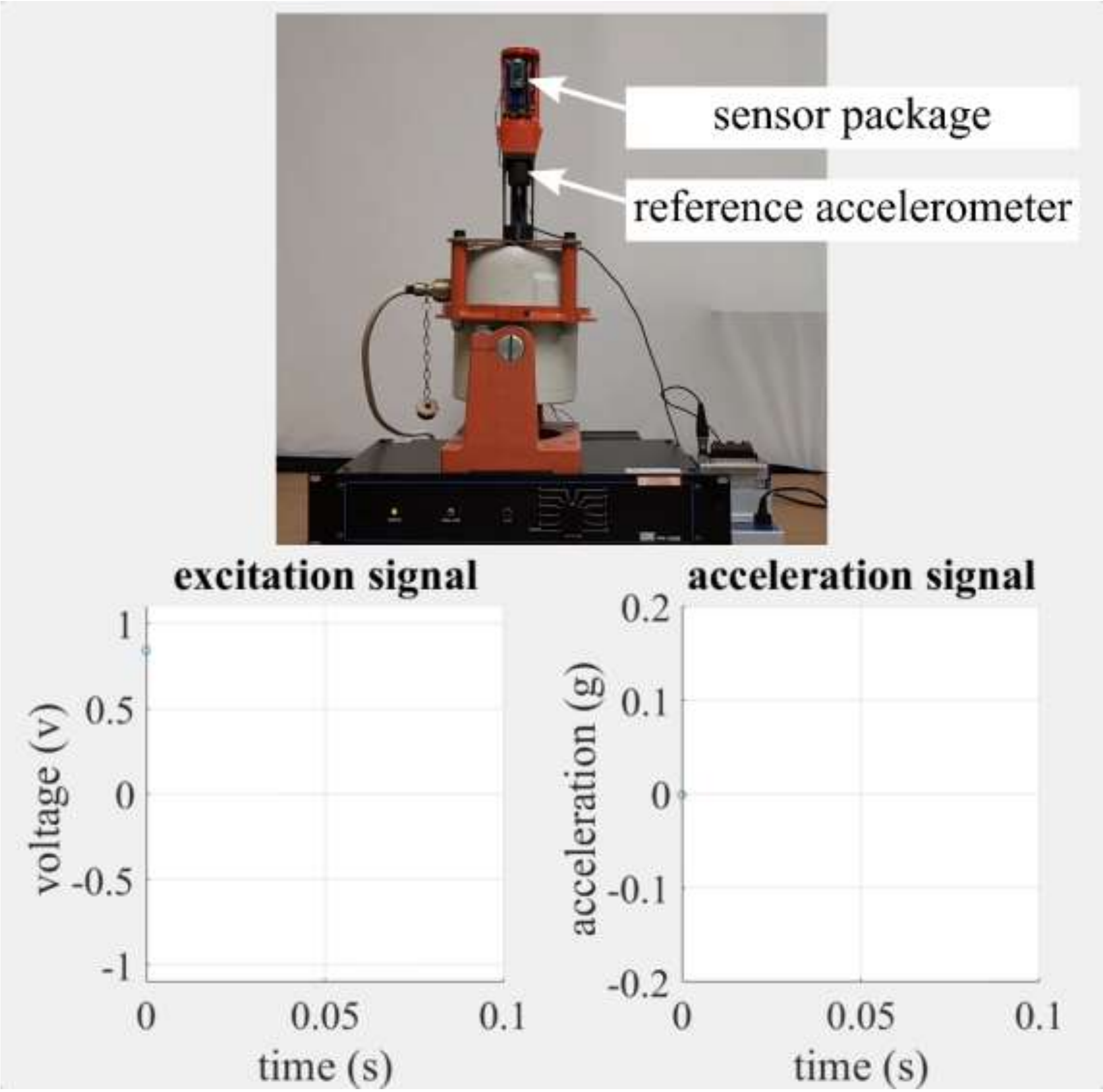
Signal Conditioning and Error Compensation

- 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

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

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

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

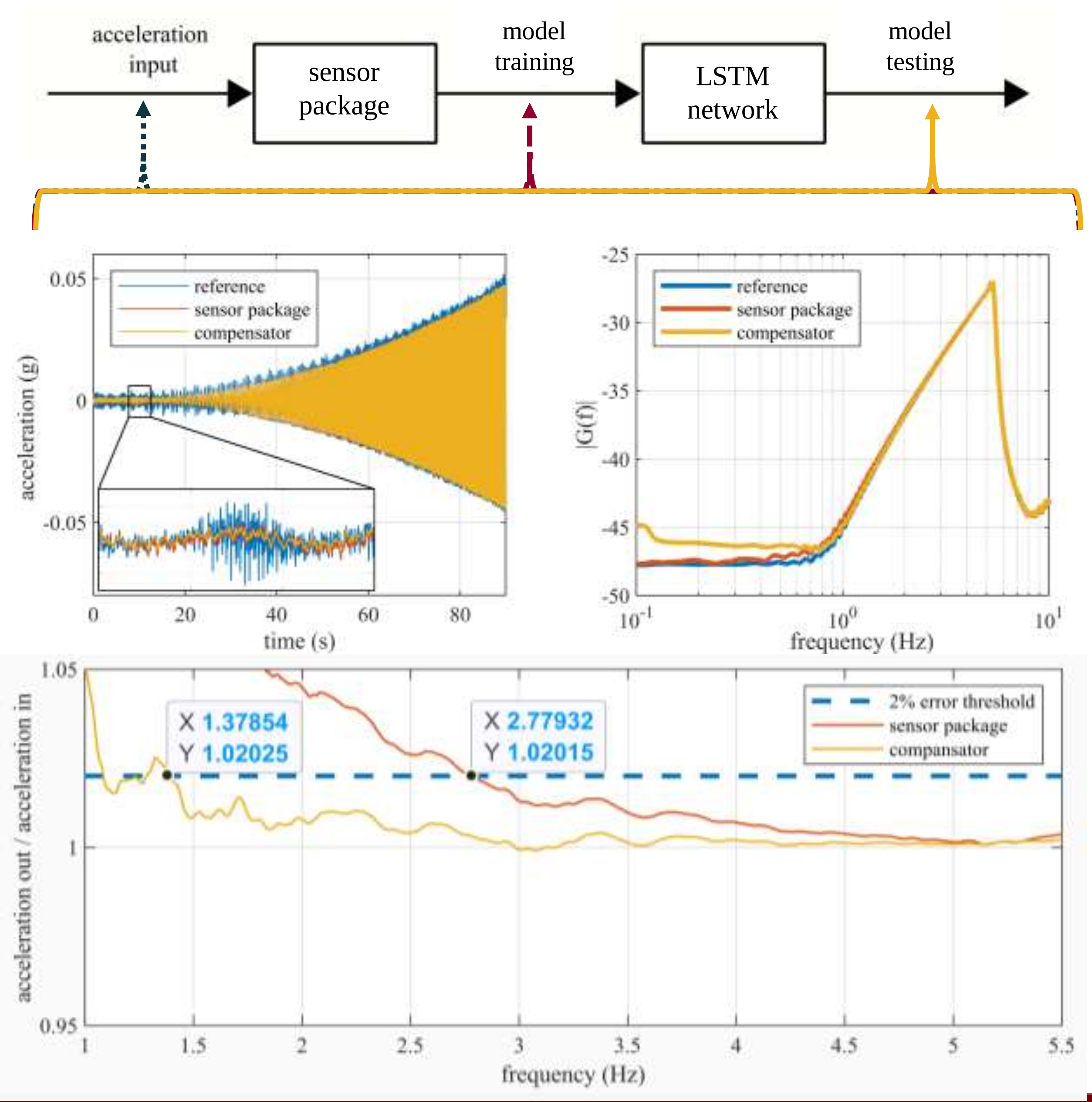


LSTM Performance

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	1.795×10^{-3}
LSTM compensator	18.88 dB	1.442×10^{-3}
% improvement	9.34%	19.66%

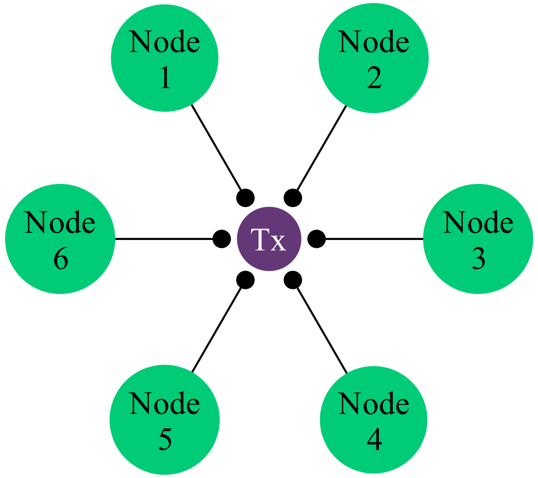


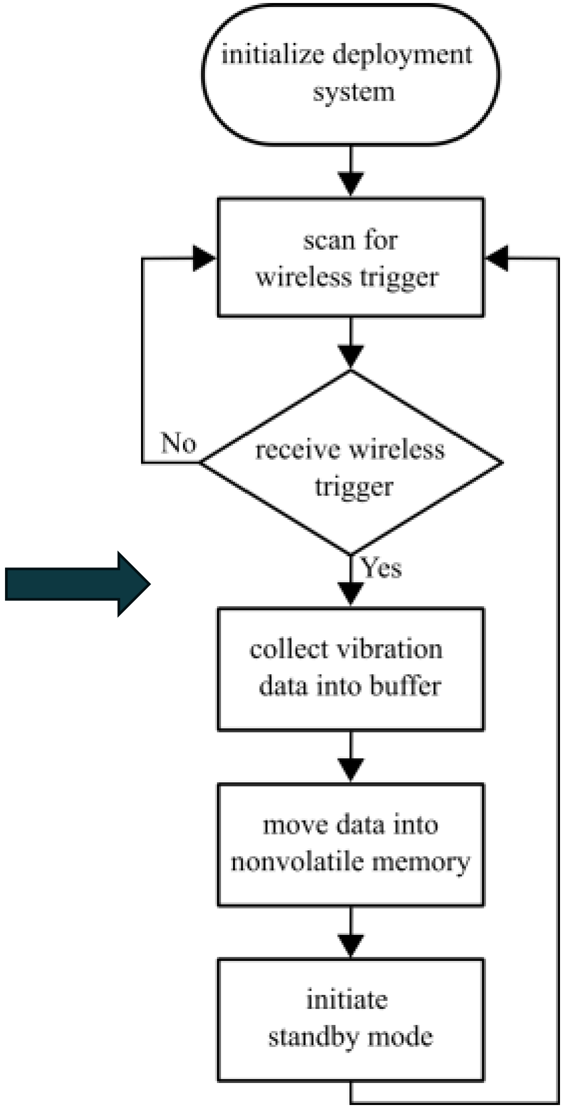
Networks of UAV-deployed Sensors

Sensing network for SHM

Wireless system:

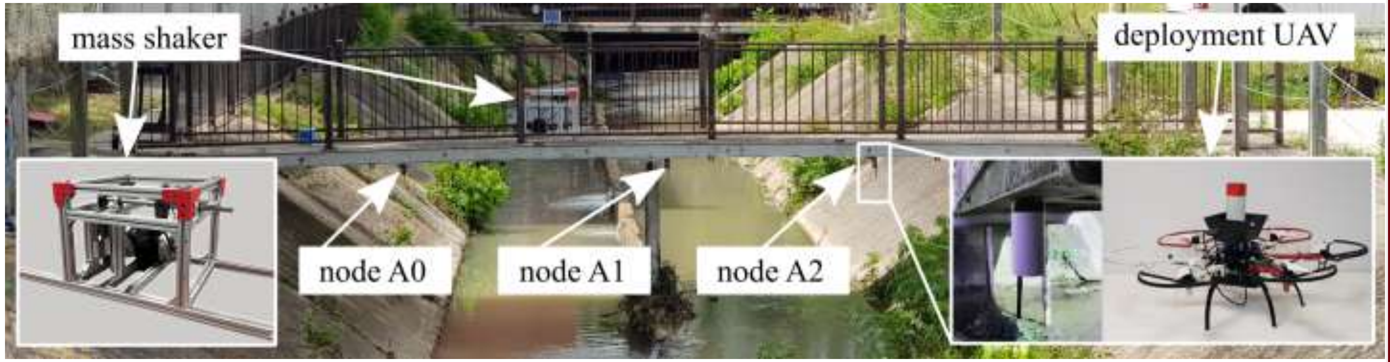
- protocol: Enhanced ShockBust
- bandwidth: 2.4 GHz
- data rate: 2 Mbps
- RF links: 6 channels

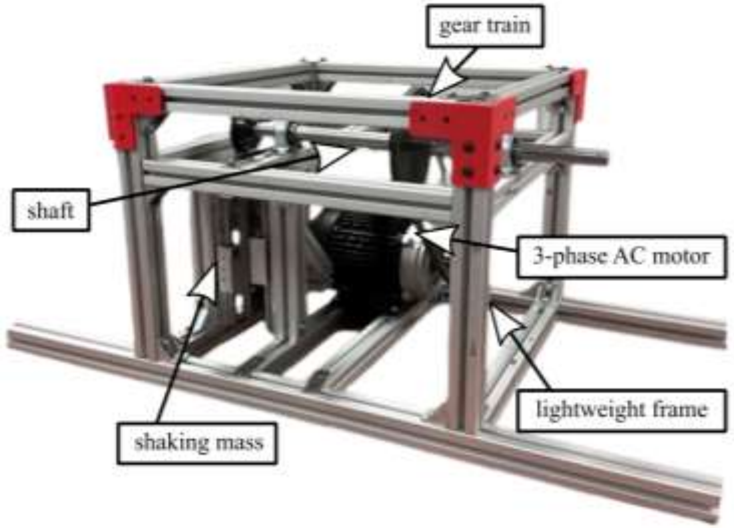


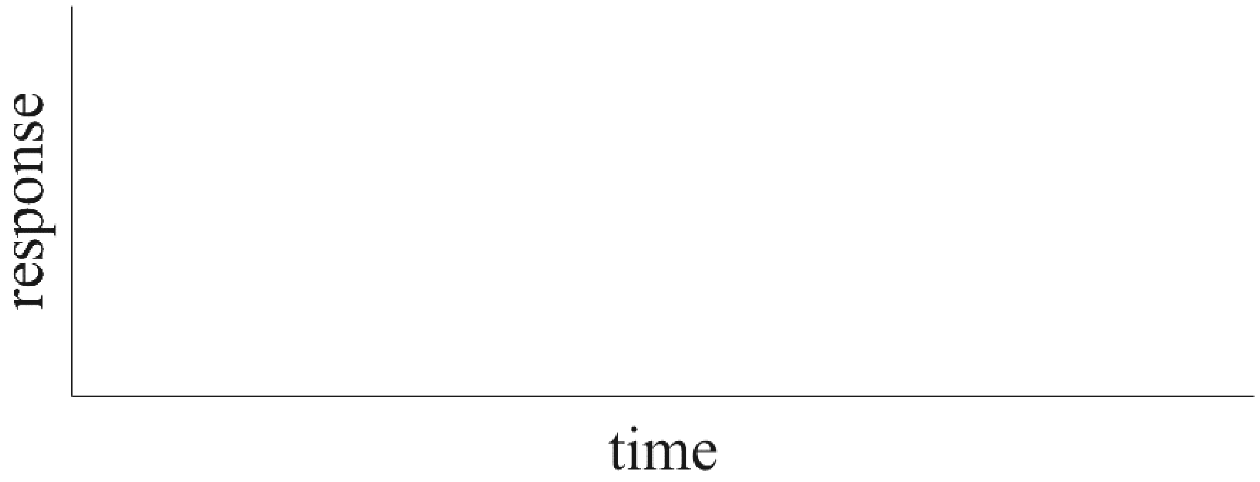


Case Study – Modal Detection

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

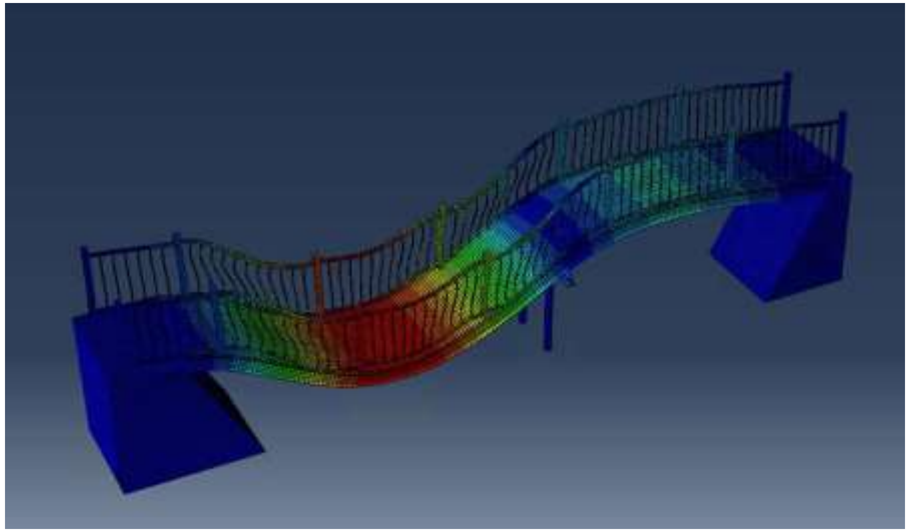




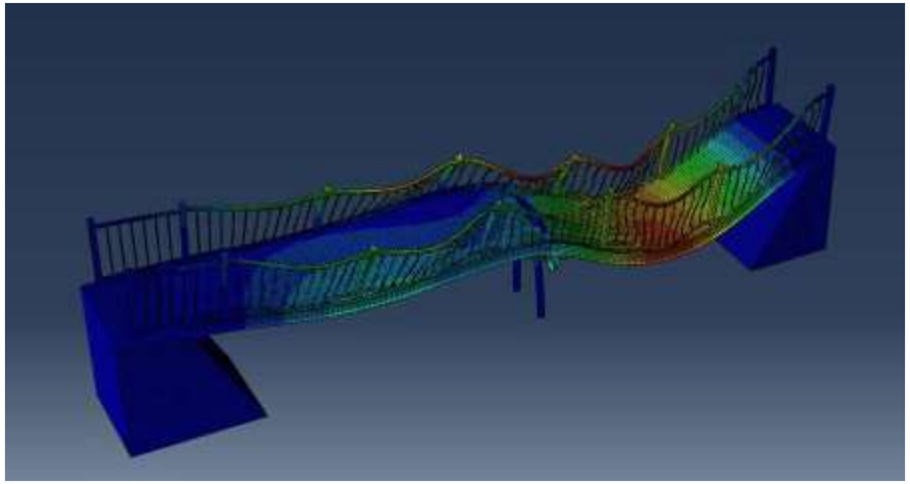


USC Waking Bridge

- **Objective:** Track and analyze bridge health using UAV-deployed sensors
- **Finite Element Analysis:** Model properties, natural frequencies, and mode shapes



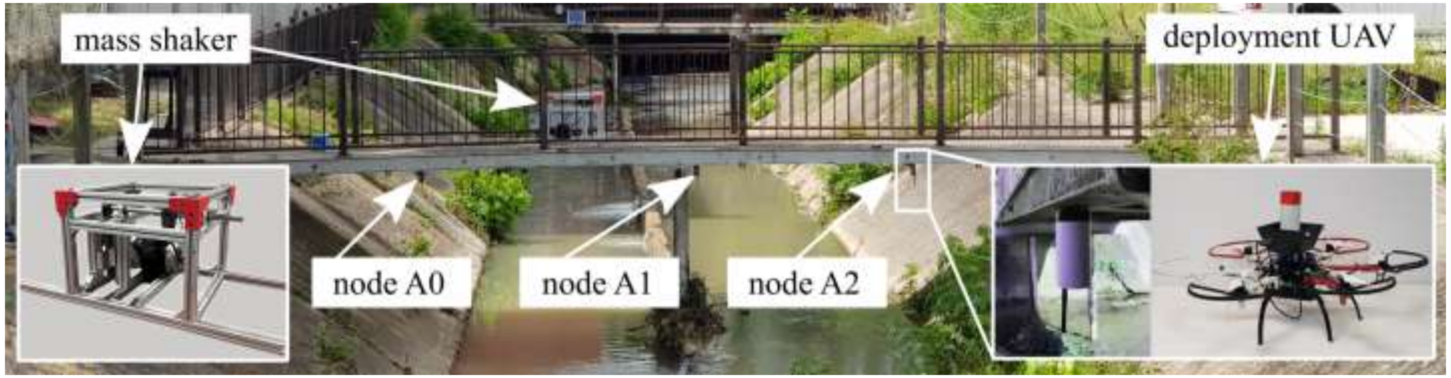
Mode 1 - 15.39 Hz

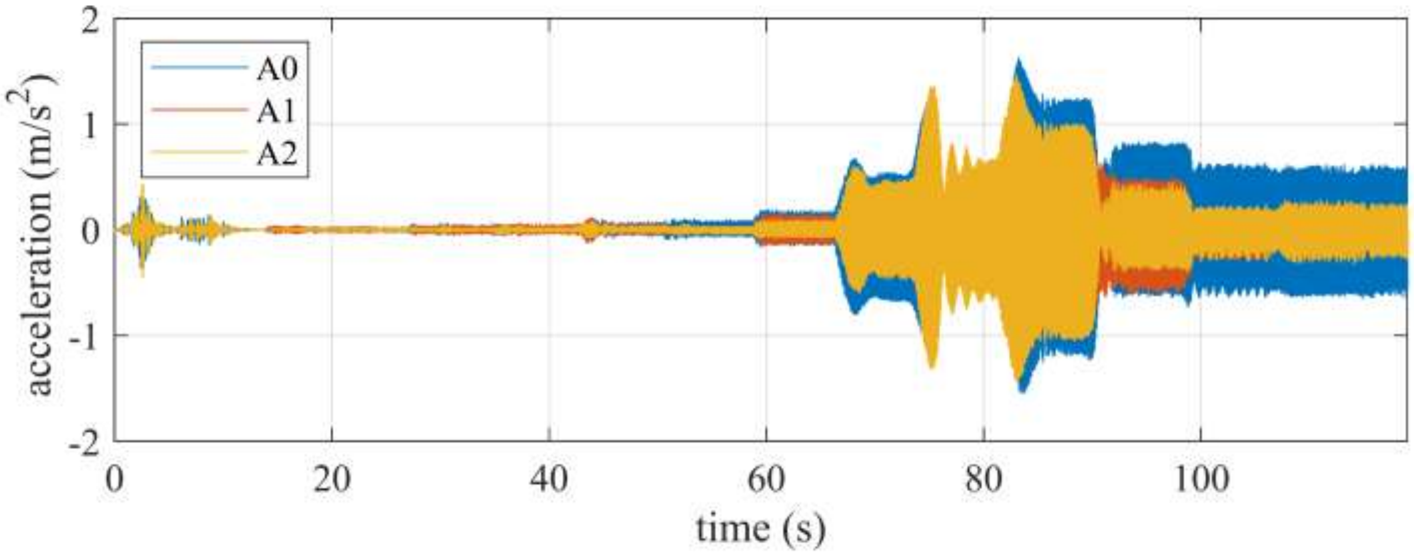


Mode 2 - 22.84 Hz

Time Response of a Pedestrian Bridge

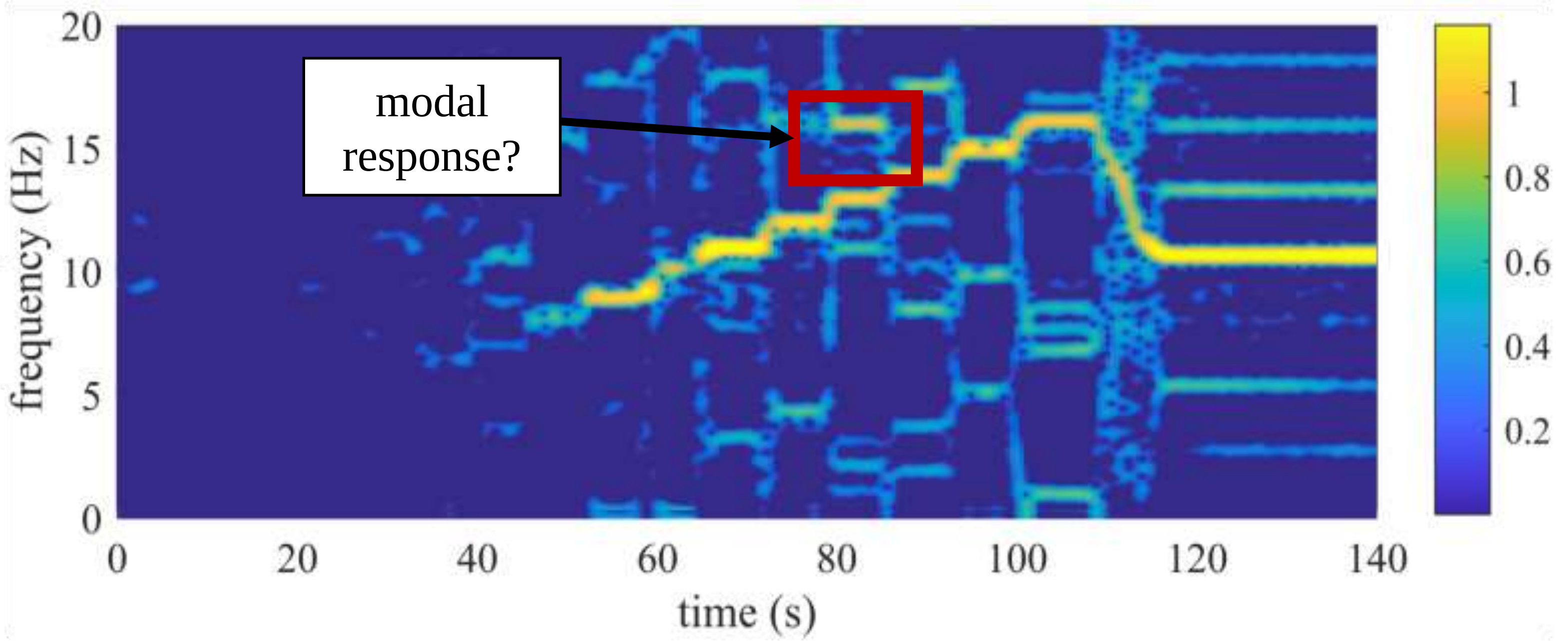
- **Test Setup:** Mass shaker and UAV-deployed sensors positioned at nodes A0, A1, and A2
- **Objective:** Capture acceleration data across key nodes for modal analysis
- **Results:** Real-time acceleration data reveals dynamic response patterns across nodes





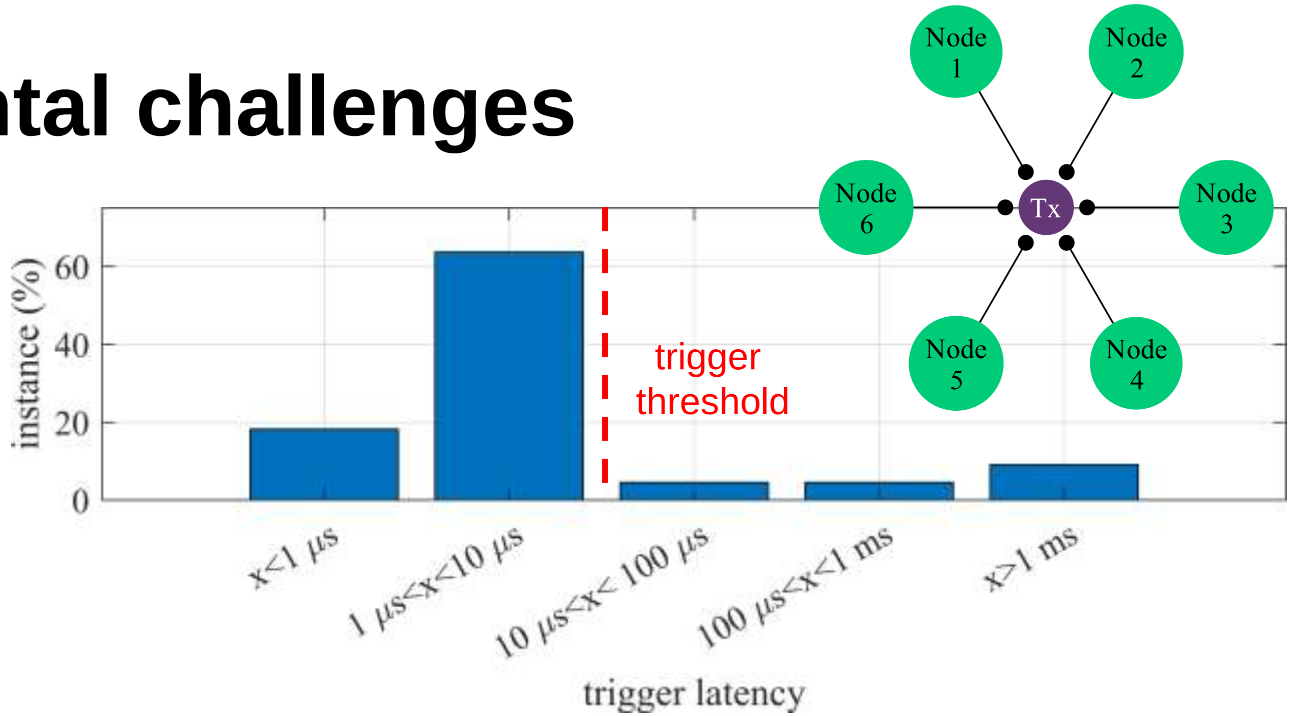
Frequency Response of a Pedestrian Bridge

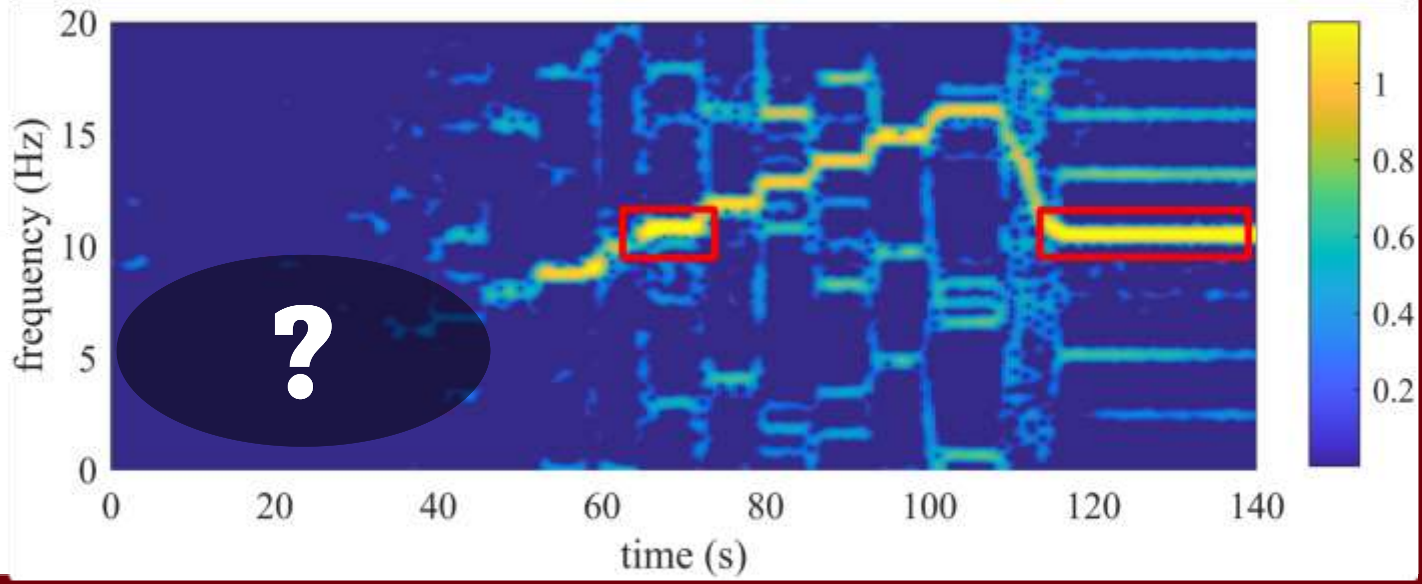
- **Setup:** Data collected from three sensor nodes deployed on bridge
- **Frequency Sweep:** 0 to 15 Hz to capture modal responses
- **Peak Detection:** Observed resonance at ~11 Hz indicating first flexural mode



Sensing system experimental challenges

- **Latency Threshold:** Set at 10 µs to maintain signal alignment across sensors
- **Latency Results:** 85% of instances fell below the threshold, improving synchronization
- **Low-Frequency Detection:** Limited by buffer size; mitigation options include extended sampling and data combination

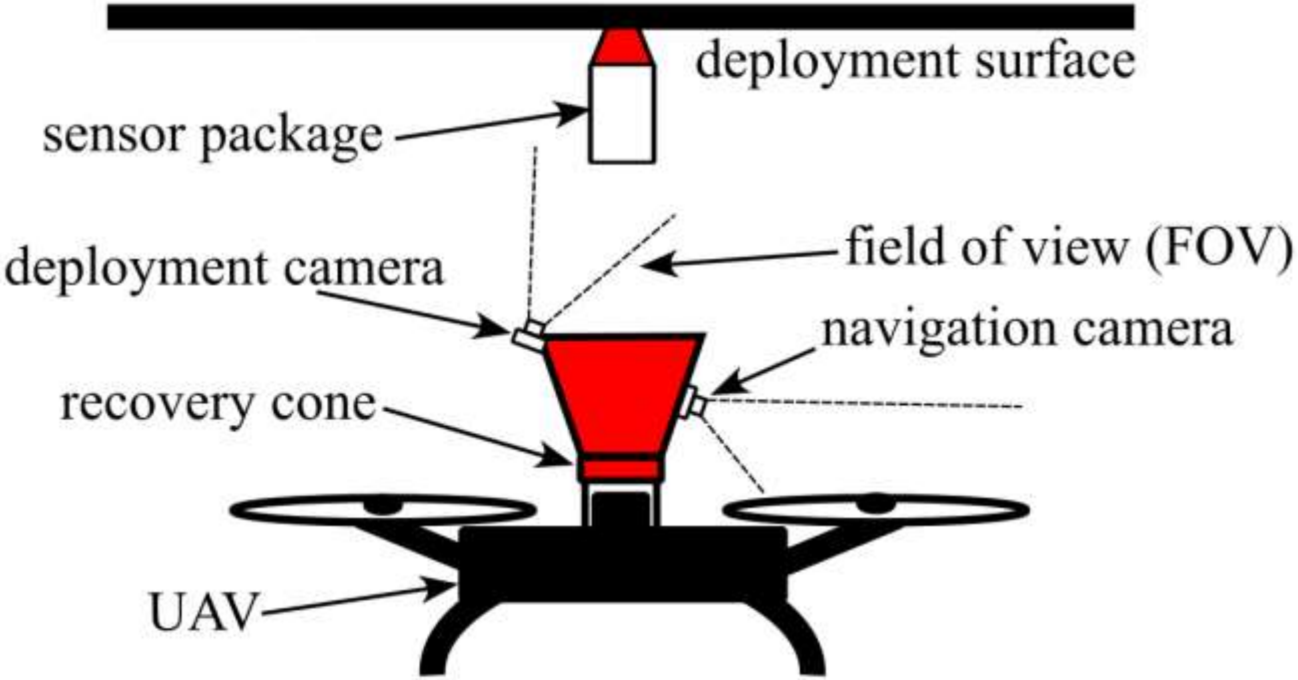




Future Directions and Preliminary Results

Camera-Assisted Navigation and Alignment

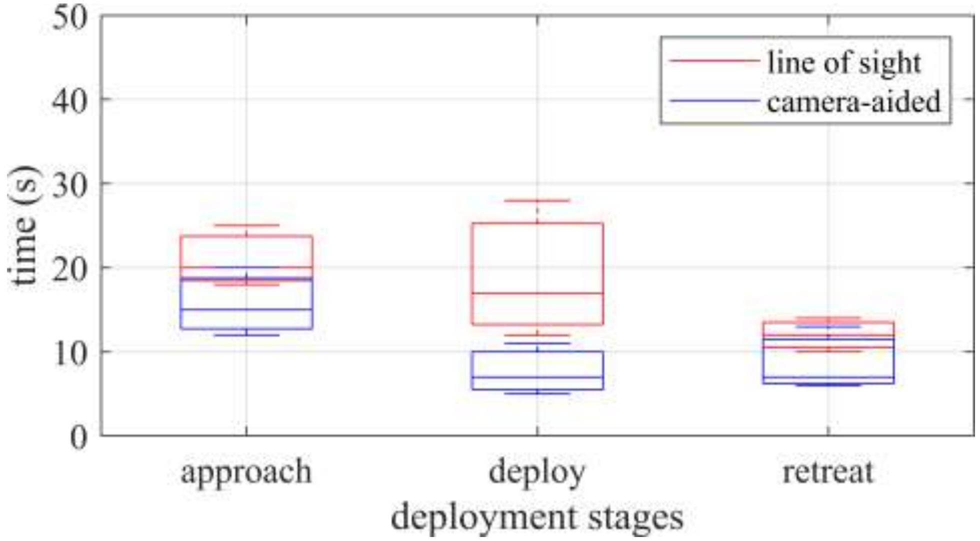
- **Multi-Camera Setup:** Provides real-time spatial awareness for precise navigation.
- **Target Identification:** Assists in locating the sensor package with visual feedback.
- **Accurate Alignment:** Guides the UAV to align the recovery cone with the sensor package.
- **Foundation for Autonomy:** Key step towards a fully autonomous UAV system.

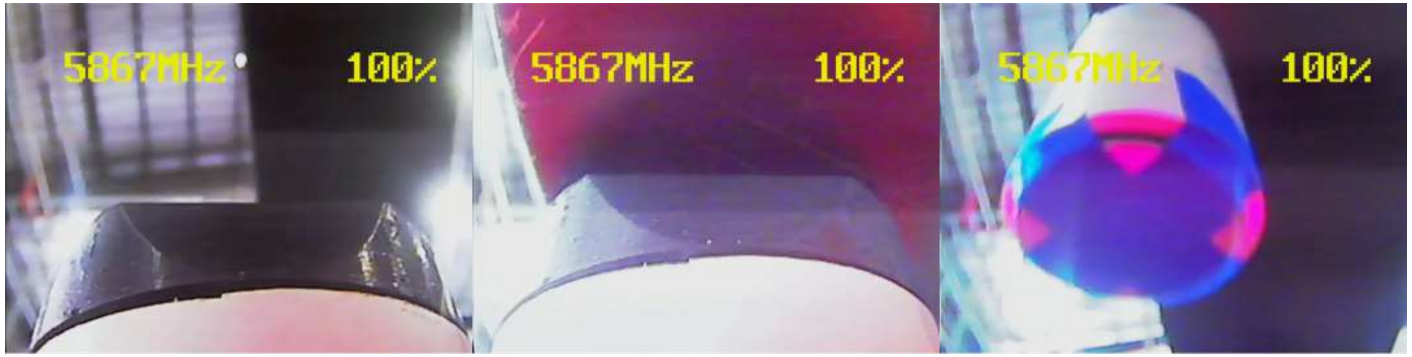


Camera-Assisted Navigation and Alignment

Experimental Insights and Preliminary Success

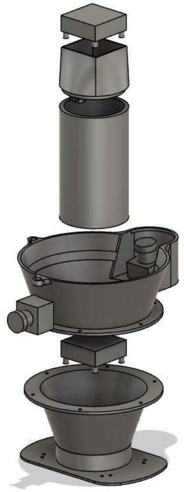
- **Camera-Aided Navigation:** Enhances spatial awareness during approach, deployment, and retreat.
- **Efficiency Gains:** Camera-assisted deployment reduces time across all stages.
- **Improved Precision:** Minimizes failed approaches and unintended contact.

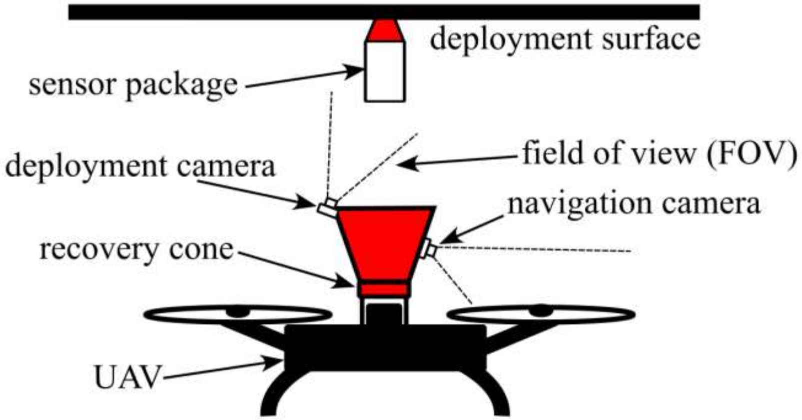




Future Work

- **Automate Delivery:** Enable precise, autonomous sensor deployment and retrieval with minimal human input.
- **Improve Streaming:** Boost video quality for better navigation.

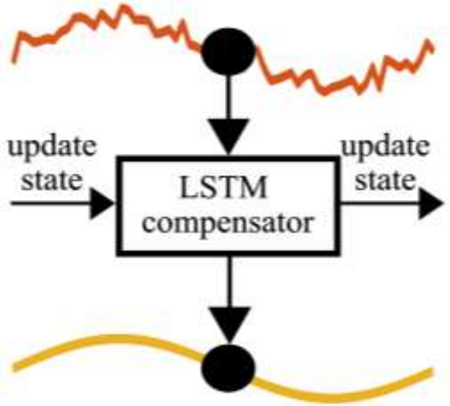


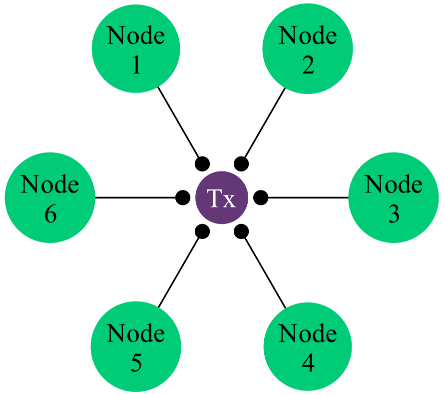


Conclusion

Conclusion

- **Key Achievements:** UAV-deployable sensor with autonomous alignment
- **Enhanced Data Quality:** Real-time LSTM signal compensation
- **Future Goals:** Full autonomy and robust field deployment





Questions and Discussion

Key GitHub Repositories

- **Sensor Package:** https://github.com/ARTS-Laboratory/Drone-Delivered-Vibration-Sensor
- **Docking System:** https://github.com/ARTS-Laboratory/UAV-Package-Delivery-System
- **Bridge Data:** https://github.com/ARTS-Laboratory/USC-walking-bridges

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