Edge Processing for Frequency Identification on Drone-Deployed Structural Health Monitoring Sensor Nodes

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Methodology
Experimentation
Results and Discussion
Future work

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- Methodology:
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  - Sensor algorithm
- Experimentation:
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  - Structure testing
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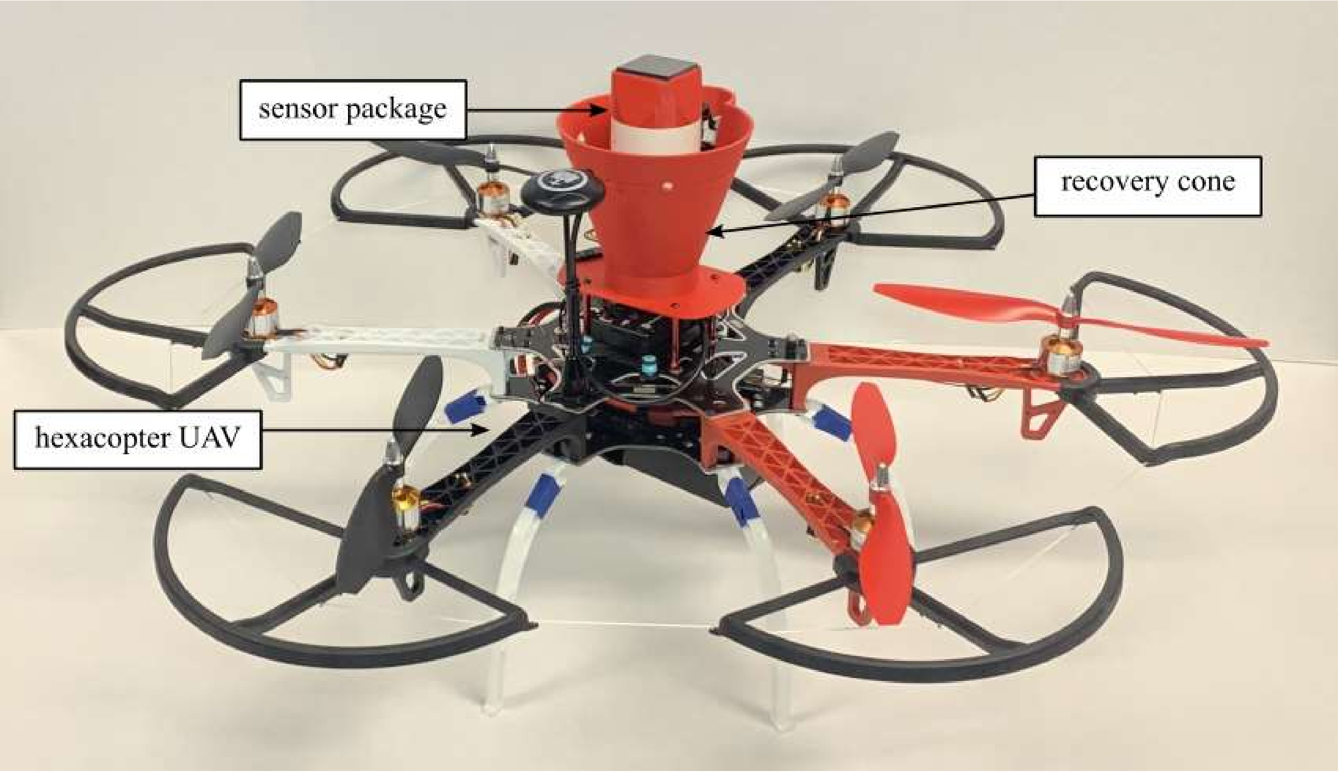
- Future work:
  - Sensor improvement



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Introduction

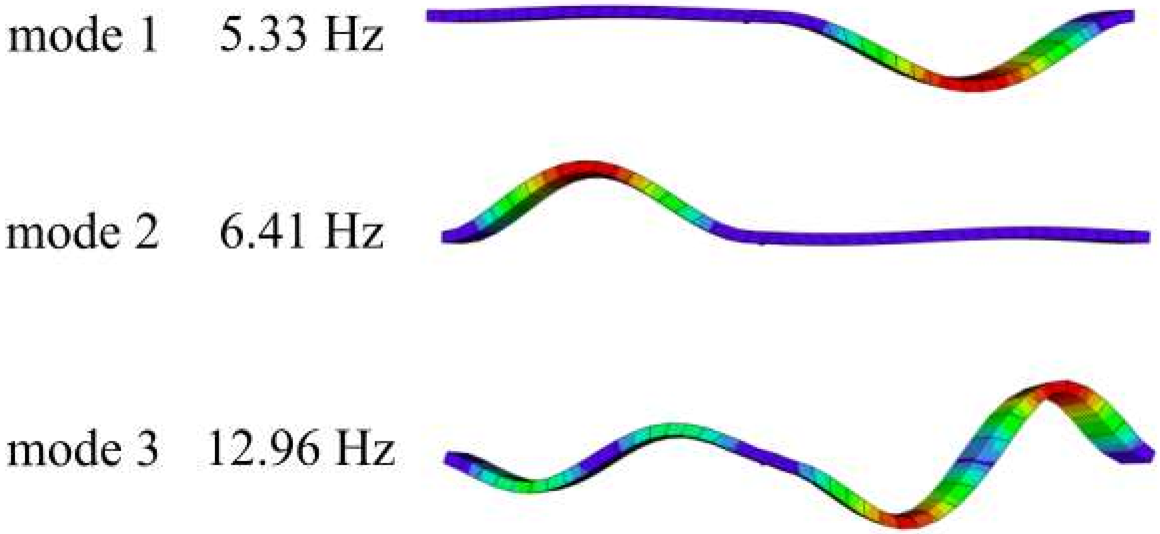
- Importance in structural health monitoring:
    - Accelerometers are used to observe how vibrations propagate in structures
- Problem statement:
    - Traditional SHM relies on off-site computational analysis
    - Can cause delays in data processing and transmission
    - No real-time insights
- Proposed approach:
    - Sensor package with frequency computation on the edge
    - UAV-delivery system
    - Open-source


https://dunganeng.com/about-dungan/our-company/


https://www.globalwaterforum.org/2022/11/10/mind-the-gap-between-perception-and-reality-of-bridge-collapses-over-water/

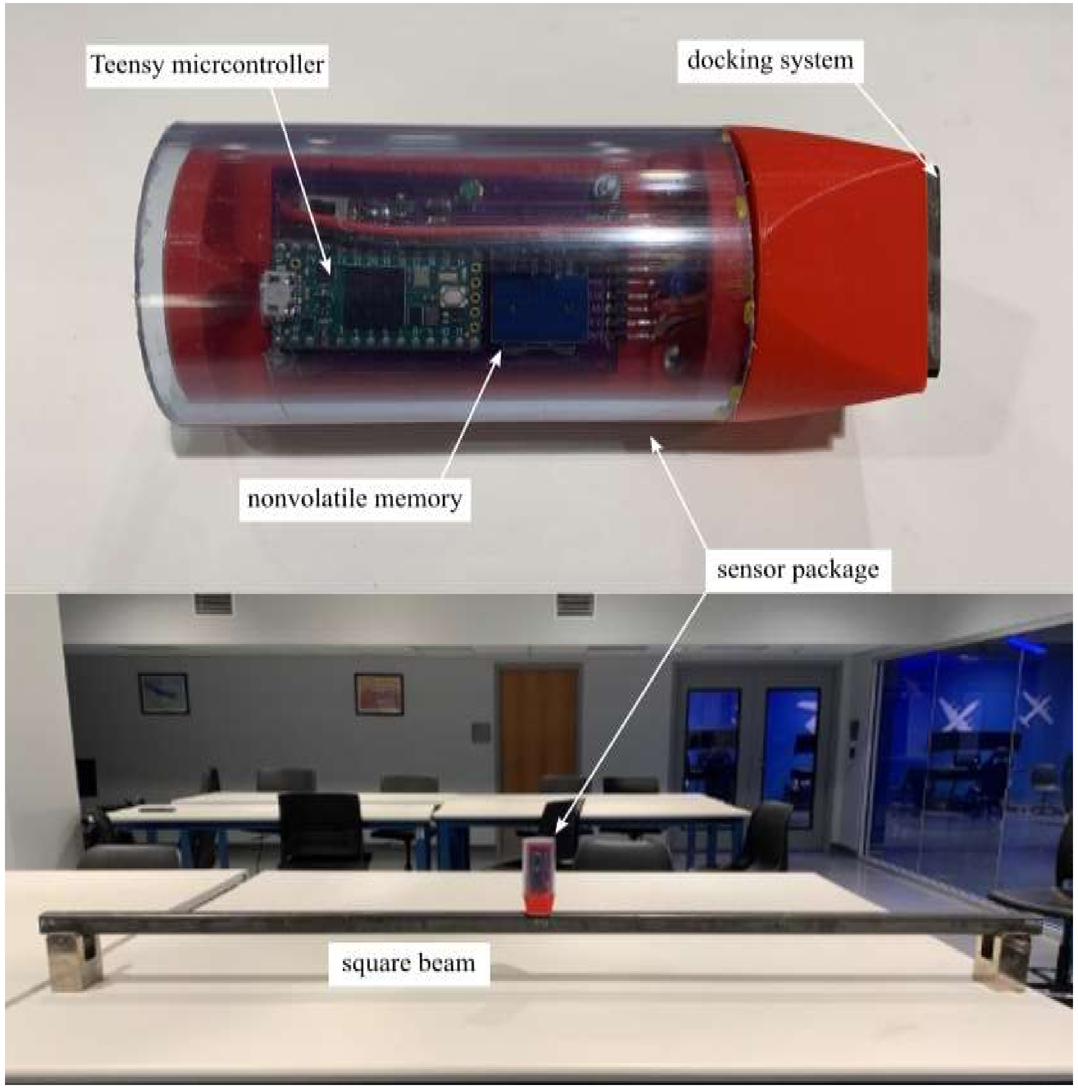
Methodology

- These sensor packages can be used to detect damage states
- For this, modal frequencies would need to be known beforehand so that the sensor could detect that something is wrong
  - For example: a model of a pedestrian bridge
- A sensor that can calculate modal frequencies on the edge is then useful to detect any differences in what is expected



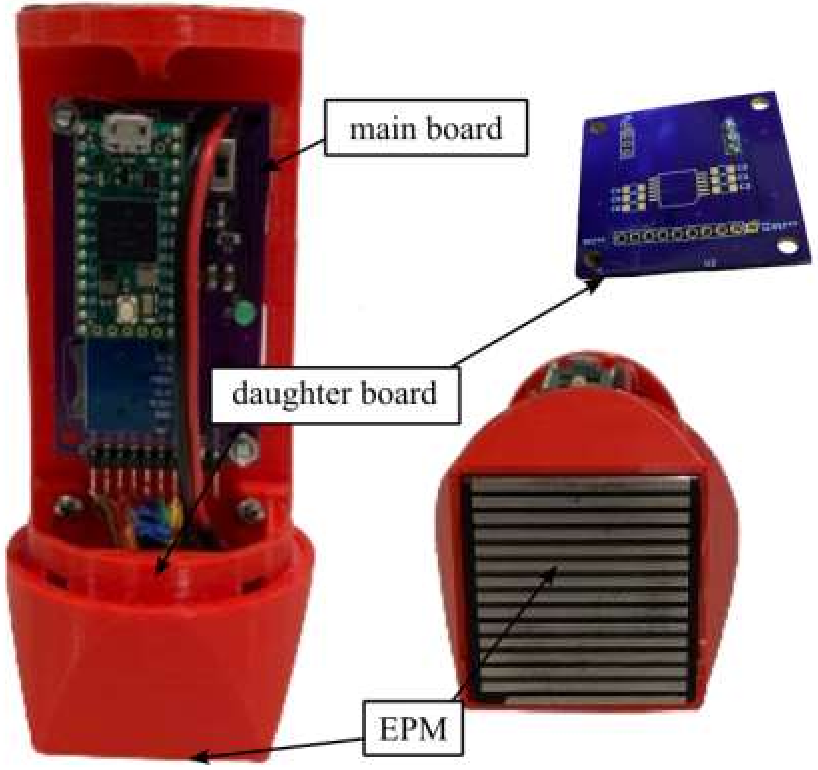
Sensor package breakdown

- Features:
    - Designed for high mobility UAV-deployment.
    - Equipped for extended deployment with power and memory subsystems.
    - Wireless subsystem for triggering and IO commands.
    - Docking subsystem utilizing electropermanent magnets.
    - Lightweight frame optimized to reduce transmission losses.
    - Data capture up to a sampling rate of 28 kS/s.
    - On board edge processing for modal frequencies.



Sensor package breakdown

- Hardware:
  - 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.
  - 1500mAh 2-cell lithium polymer battery, voltage regulation and monitoring.
  - NRF24L01 Nordic Semiconductor wireless transceiver.
  - DS3231 real-time clock (RTC) for data logging and trigger time reference.



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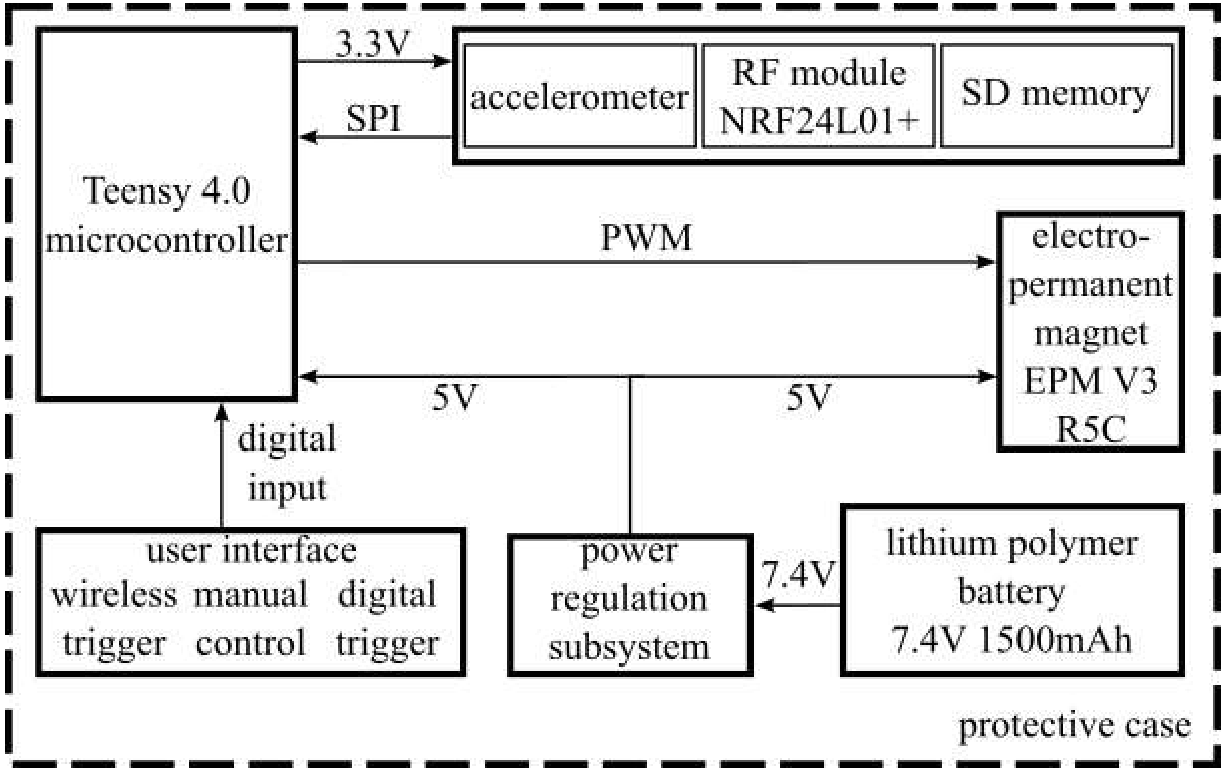
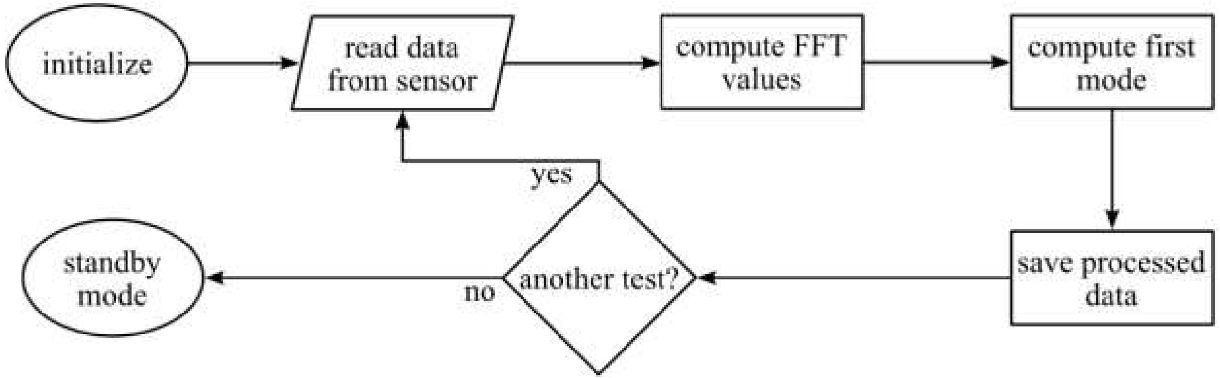


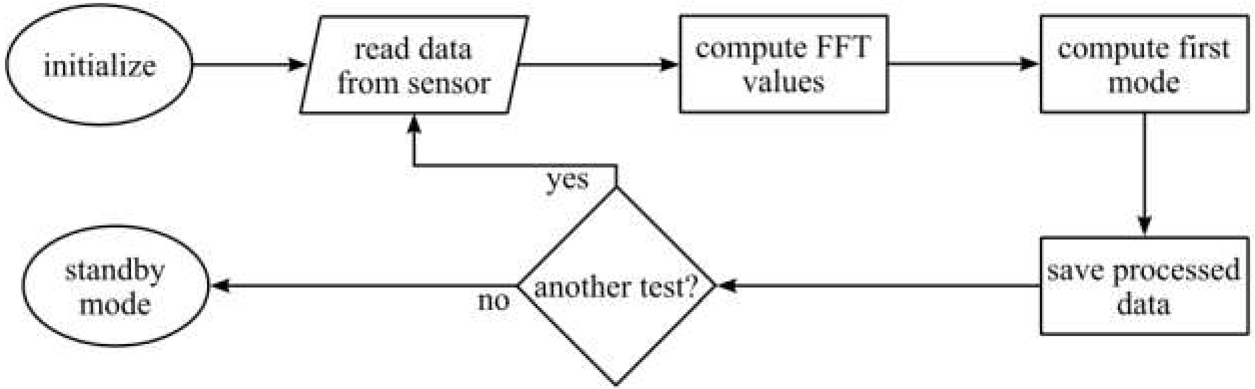
Sensor algorithm

- Edge computation for rapid data-acquisition
- Code first initializes libraries for the sensor components and sets up variables and functions for use later
- Data is read from the sensor
  - 16,384 samples
  - 1600 samples/s
- Data is stored in nonvolatile memory to clear up dynamic memory for later code



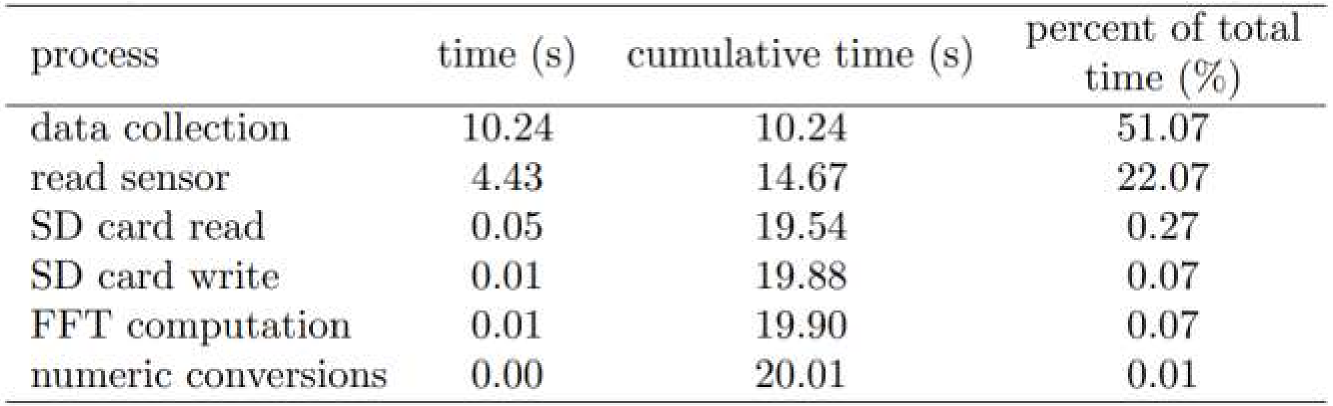
Sensor algorithm

- Post data collection, accelerometer data is accessed to compute the FFT
  - Cooley-Tukey variant
  - Data is divided into even and odd indexed points
  - Each has its own FFT then get combined
- Then, peak detection is used to record the first flexural mode of a structure
- If another test is required, it will begin at the data collection step and continue
- Otherwise, it will enter standby mode (no sensing)



Computational efficiency testing

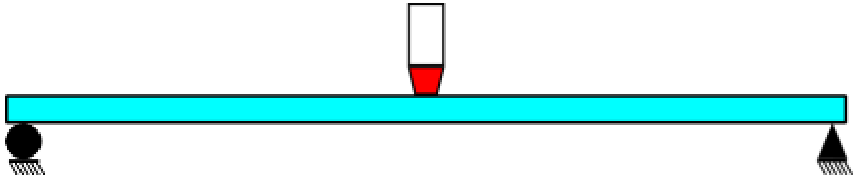
- Teensy 4.0 has ample memory for complex computations
- The Arduino toolchain is used for stable, continuous operation
- Hardware performance is profiled using GNU gprof
    - Insights into execution times
- Data collection is the most time-consuming because it is at a set time
- The timing analysis was focused on crucial functions of the algorithm’s performance
- 30 benchtop profiling runs were executed with consistent results

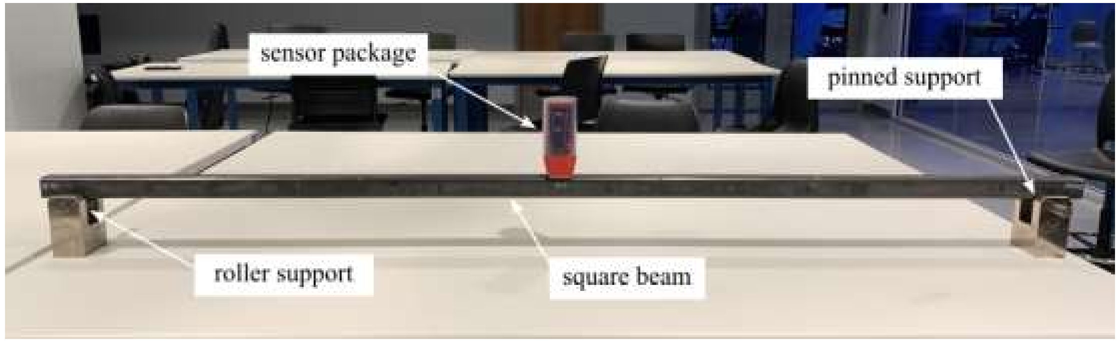


process	time (s)	cumulative time (s)	percent of total time (%)
data collection	10.24	10.24	51.07
read sensor	4.43	14.67	22.07
SD card read	0.05	19.54	0.27
SD card write	0.01	19.88	0.07
FFT computation	0.01	19.90	0.07
numeric conversions	0.00	20.01	0.01

Structure test

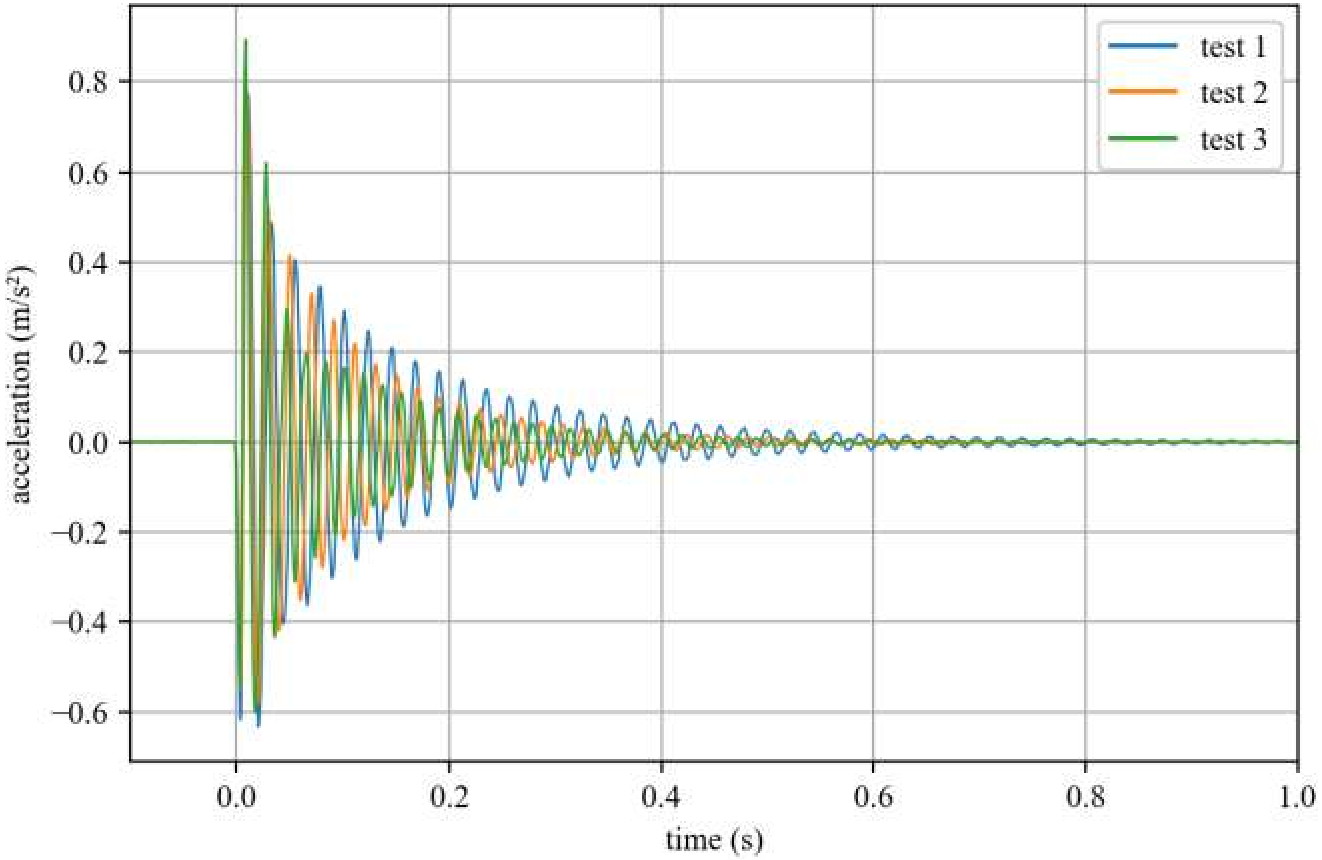
- Investigated vibrational behavior of a square stock beam with pinned and roller supports
- The primary goal was to assess the sensor's ability to measure across varying structural conditions
- A single sensor package was positioned in the center of the beam
- A series of three tests were performed, each intended to simulate a different structural state
    - Initially, both supports start evenly spaced from the center of the beam
    - After the first test, the left roller support was moved closer to the center incrementally





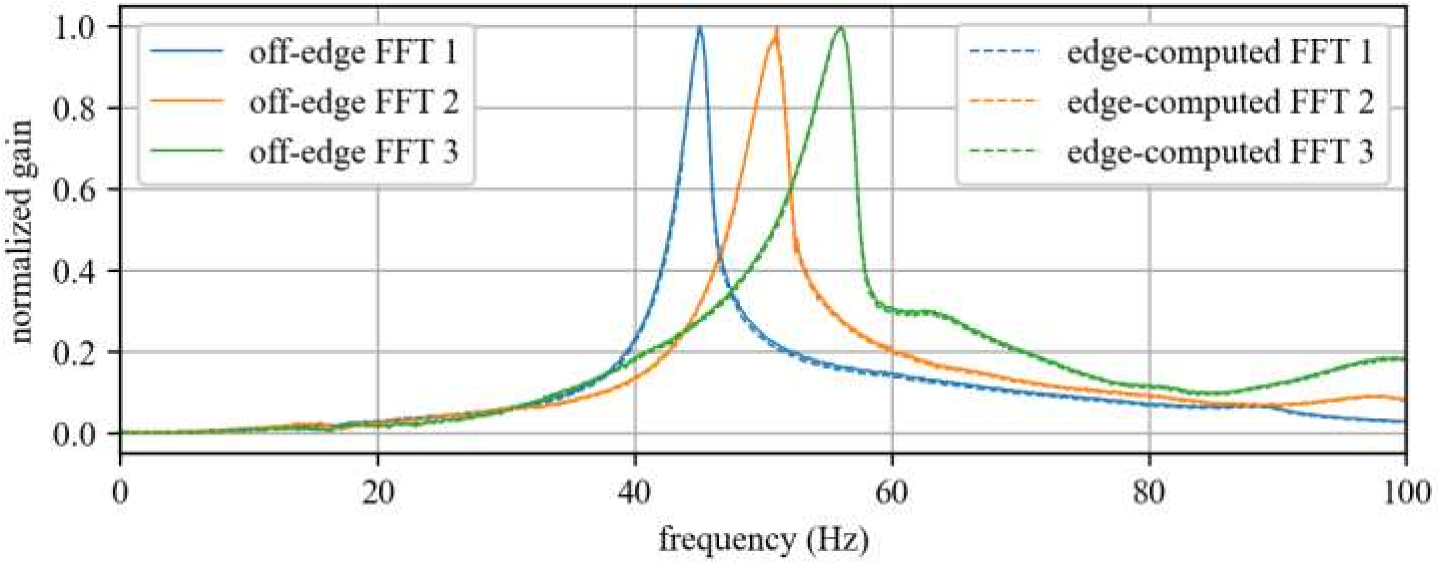
Structure test

- A modal impact tool was used to create an impulse response in the beam
- During each test, the sensor package continuously recorded vibration data from the beam
- Each subsequent test shows a faster damping rate than the test before it
  - Showcases the sensor’s ability to read different structural states
- The collected data was then subjected to FFT analysis
- The primary focus was to identify the first modal frequency of the system



Experimental outcomes

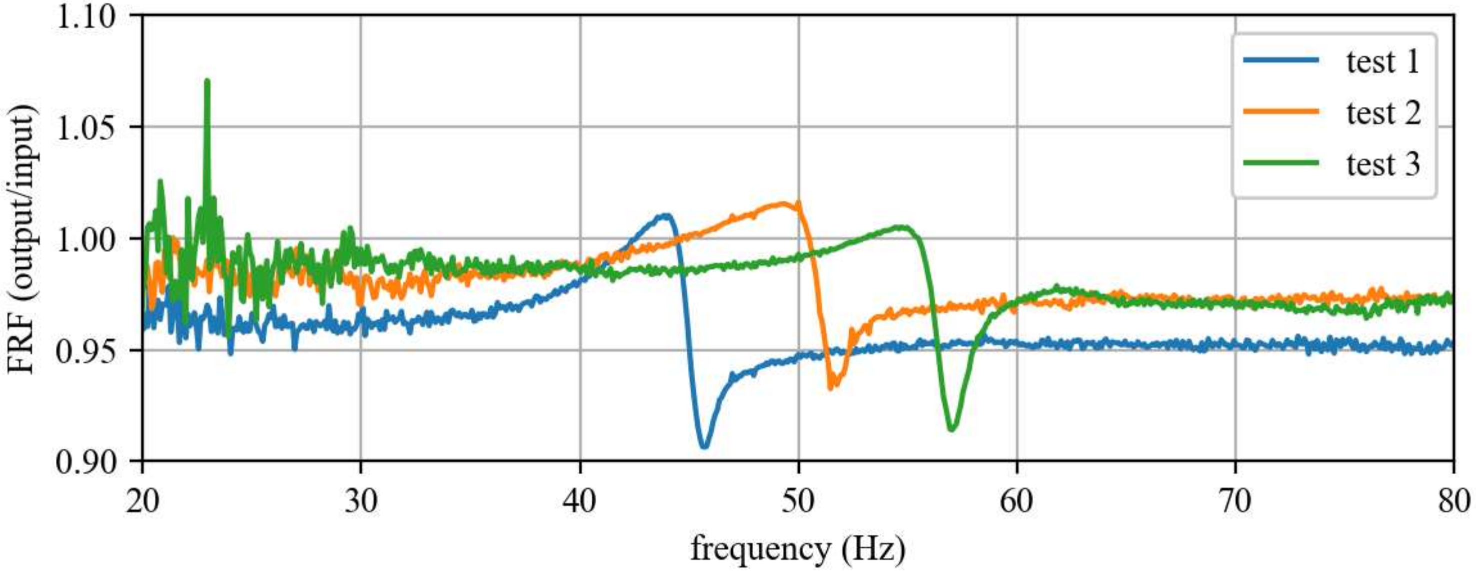
- The sensor was able to run the FFT successfully and determine the first modal frequency of the system
  - Test 1: 45.1 Hz
  - Test 2: 51.0 Hz
  - Test 3: 56.0 Hz
- An offsite FFT calculation was made to compare the precision of the sensor's algorithm
  - RMSEs: 0.0032, 0.0028, 0.0031
- Offset in the natural frequency of the system can be attributed to the different structural states



● Mode 1 Frequency: 45.1 Hz ● Mode 1 Frequency: 51.0 Hz ● Mode 1 Frequency: 56.0 Hz

Experimental outcomes

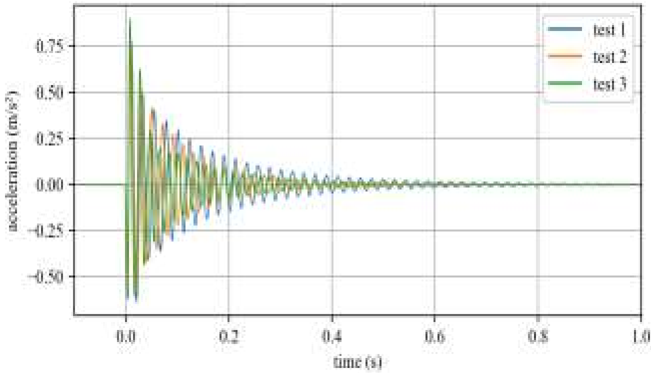
- A frequency response calculation was made to determine how close the FFT run by the sensor package was to the offsite FFT
- Ideally, the FRF should be flat, indicating the sensor FFT is calculated with the same precision as an offsite program
- Around the three calculated modes, the largest difference is 0.906/1 giving a percent error of around 9.4%



Conclusions and Overview

- Examined an open-source high-mobility edge processing sensor package for structural health monitoring
- Holds potential as a useful tool for vibration analysis
- Well-suited for UAV-deployment in challenging or human-inaccessible areas
- Enables quick deployment for rapid assessment
- Limitations:
  - Sensor requires physical retrieval for data viewing
  - FFT and peak finding code had to be optimized for space on the microcontroller

- **Future work**
  - Sensor improvement
    - Improve sensor algorithm
      - Continuous testing
      - Compare previous modal frequencies
  - Develop a waystation to be able to read data from the sensor package off-site in real-time
    - Receive data wirelessly from a sensor package
    - Communicate with multiple sensor packages



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Drone-Delivered-Vibration-Sensor

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https://github.com/ARTS-Laboratory/Drone-Delivered-Vibration-Sensor

Thank you

Questions?

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