Experimental Validation of UAV-Deployed Edge Sensors for Frequency-Based Bridge Damage Detection

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ABSTRACT

This work presents the experimental validation of a UAV-deployable wireless sensor package capable of edge-based Fast Fourier Transform (FFT) processing for frequency-based Structural Health Monitoring (SHM). The sensor system executes onboard computation to detect shifts in natural frequencies, enabling rapid assessment without relying on continuous high-bandwidth communication. A lab-scale beam structure is used to simulate structural state changes by repositioning support locations, with a UAV-deployable sensor placed on the beam to capture vibration data alongside a reference accelerometer. The embedded FFT algorithm performs local signal transformation and peak detection, successfully identifying modal frequency shifts correlated with altered boundary conditions. These peak frequencies are logged and prepared for selective wireless transmission to reduce power and data transmission demands. The sensor package is shown to reliably detect frequency shifts of approximately 1 Hz across configurations. This demonstration underscores the viability of low-power, autonomous edge-sensing systems for scalable, rapid-deployment SHM platforms, particularly when structural access is constrained or latency is critical.

INTRODUCTION

Structural Health Monitoring (SHM) is a critical process for assessing the integrity of infrastructures, typically involving the deployment of wired sensors and dedicated monitoring hardware [1]. These conventional systems, while accurate, often require access to hazardous or difficult-to-reach areas and rely on trained personnel for installation and operation [2]. As a result, they can be slow to deploy, costly to maintain, and impractical during emergencies or for aging infrastructure located in remote environments. After natural disasters, prompt and precise estimation of structural damage is critical to ensure public safety and efficient recovery [3].

Traditionally, SHM methods are based on the physical examination of deteriorating and unstable structures, which can be hazardous, especially after extreme weather conditions. These methods are also labor-intensive and time-consuming, introducing delays

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to the decision-making processes. Therefore, there is a pressing need for efficient and safe SHM solutions, especially in situations where rapid damage assessment is critical to public safety.

Edge-computing offers a solution for structural health monitoring by enabling real-time data processing directly on the sensing device, which reduces reliance on external computation resources and minimizes communication bottlenecks. These methods have been shown to significantly reduce the volume of data transmitted in computer vision-based structural health monitoring [4], thereby decreasing processing time for prognostics and enabling faster response.

To address this limitation in vibration-based sensing systems, we propose an embedded algorithm capable of performing structural diagnostics directly at the edge. The algorithm computes the frequency response in situ and extracts modal parameters, enabling the system to detect shifts in a structure's modal frequencies that may indicate damage or degradation [5]. By embedding this processing capability within the sensor node itself, the approach eliminates the need for high-throughput communication and post-deployment data analysis, streamlining SHM workflows and enhancing the responsiveness and autonomy of UAV-based sensing platforms. The contribution of this work ia a comparative analysis of the developed hardware/software solution with a high-fidelity reference accelerometer to validate the algorithm's ability to 1) accurately identify modal frequencies, despite lower amplitude fidelity, and 2) detect shifts in these modal frequencies due to altered physical properties of a structure.

BACKGROUND

Unpiloted Aerial Vehicles (UAVs) present a promising alternative to traditional structural health monitoring (SHM) approaches by enabling the deployment of wireless sensor packages, as illustrated in Figure 1. UAV-deployable sensors eliminate the need for

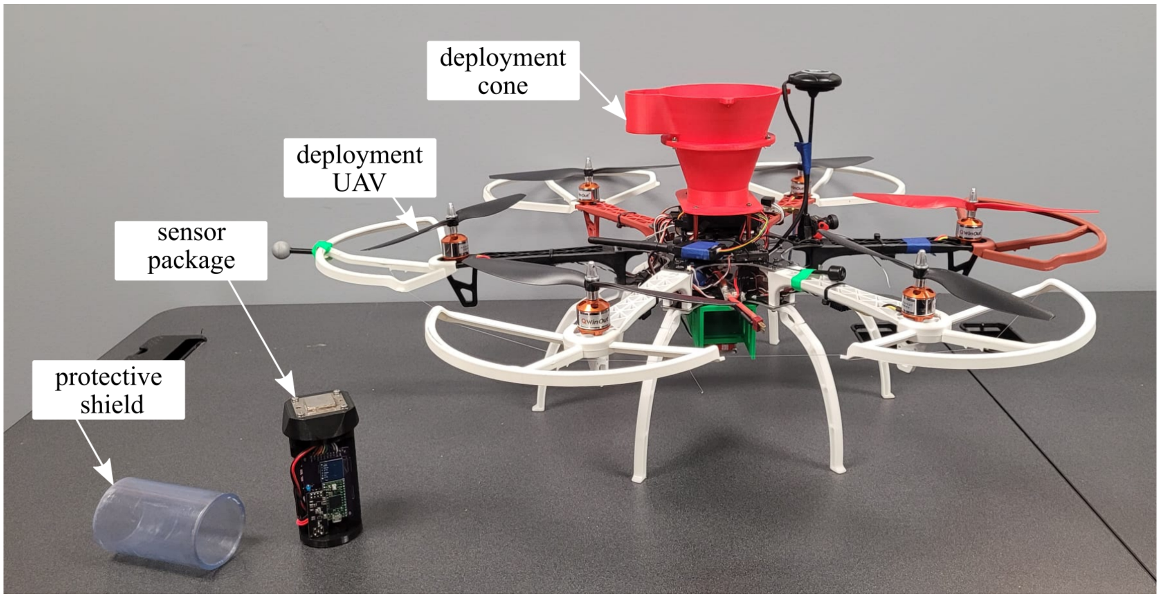

Figure 1. the UAV system along with the disassembled sensor package with key components annotated.

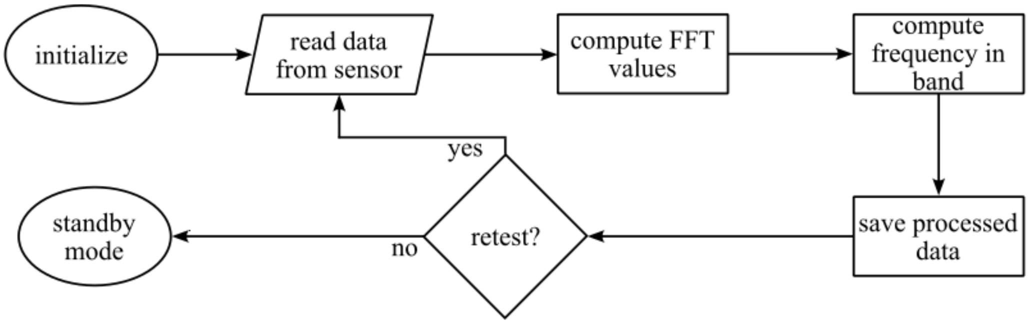

Figure 2. Flow chart indicating the basic sequence of operations for the sensor package when testing for frequencies.

manual placement in hazardous locations, facilitate rapid post-event assessment (e.g., after earthquakes or floods), and offer high mobility at relatively low cost [6]. This aerial sensor delivery system, developed by the authors, supports flexible deployment and retrieval of sensor nodes, particularly for vibration-based modal analysis applications [7].

Building on this platform, the authors have demonstrated the open-source UAV-deployable wireless sensor package specifically designed for modal-based SHM. These sensor nodes integrate onboard data processing, long-range wireless communication, and electropermanent magnet (EPM) docking to enable autonomous deployment on steel structures. Tailored for active monitoring scenarios, the system records high-resolution acceleration data during structural excitation and facilitates the identification of key dynamic properties such as natural frequencies. A case study on a pedestrian bridge confirmed the sensor's ability to capture the first flexural mode, validating the system's effectiveness for mobile, real-world SHM [8]. Despite these advantages, transmitting full-resolution vibration data to a centralized processor imposes substantial bandwidth and power burdens, making conventional post-processing approaches less practical for rapid-response scenarios.

METHODOLOGY

The edge-deployed algorithm begins by declaring variables and functions to be employed for further processing, as well as the required libraries. Accelerometer vibration data is received along with their respective timestamps. Time-domain data is saved on an SD card as a CSV file upon completion of the test. The data stored in the file is then read in and processed through an FFT in terms of an early Cooley-Tukey algorithm, in which a power-of-two-sized Discrete Fourier Transform (DFT) is decomposed recursively into smaller DFTs of the even and odd-indexed components [9]. Subsequent frequency-domain data is written to a second file to keep a record. A peak detection process is then implemented, beginning with noise removal by means of a moving average filter of a window size under user control [10]. A dynamic threshold is calculated from the mean and standard deviation of the filtered data. In a specified frequency band corresponding to an anticipated modal frequency, local maxima are found, and the highest value is selected as a modal peak. The modal frequency read is then saved to another file. A flow chart of the basic run sequence of the algorithm is shown in Figure 2.

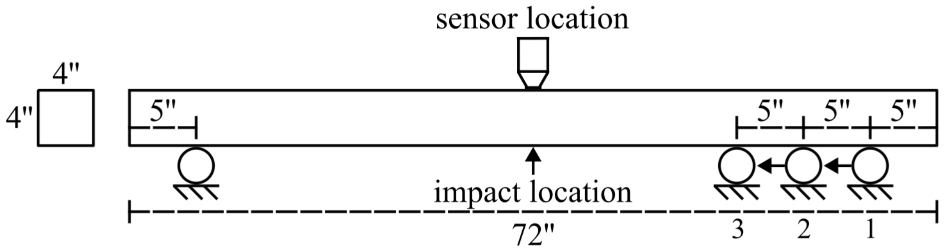

Figure 3. An illustration of the experimental setup with key components annotated.

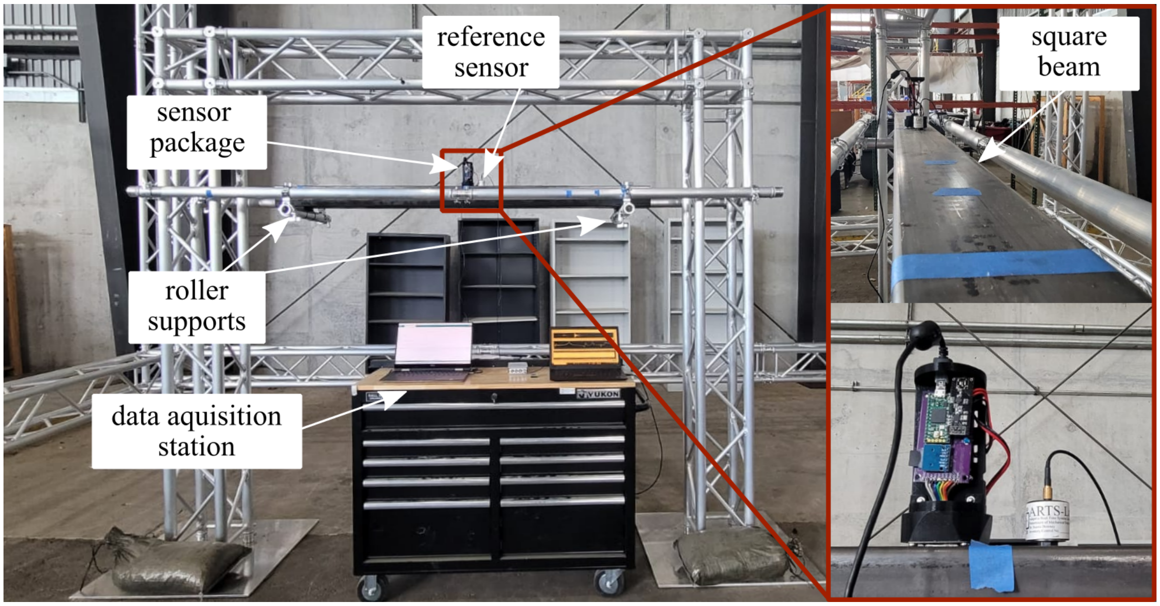

Figure 4. An illustration of the experimental setup with key components annotated.

The goal of this experiment is to assess the algorithm's ability to detect modal-frequency shifts when a structure's state is altered. A 4x4-inch steel square stock beam was supported by two roller supports, with the diagram shown in Figure 3. The system rested on a large test frame assembled from aluminum trusses (F34) as presented in Figure 4. The supports were initially positioned symmetrically, each located 5 inches from the respective ends of the beam. The sensor package was placed at the beam's center, alongside a reference accelerometer for validation purposes. A modal impact tool was used to apply a single impulse per test to excite the beam, generating time-domain vibration data. Three tests were conducted on each support configuration. After the initial tests, one of the roller supports was repositioned 5 inches closer to the beam's center, and another set of three tests was performed. Only one of the supports was moved during these tests, and this procedure was repeated twice until there were three total test configurations.

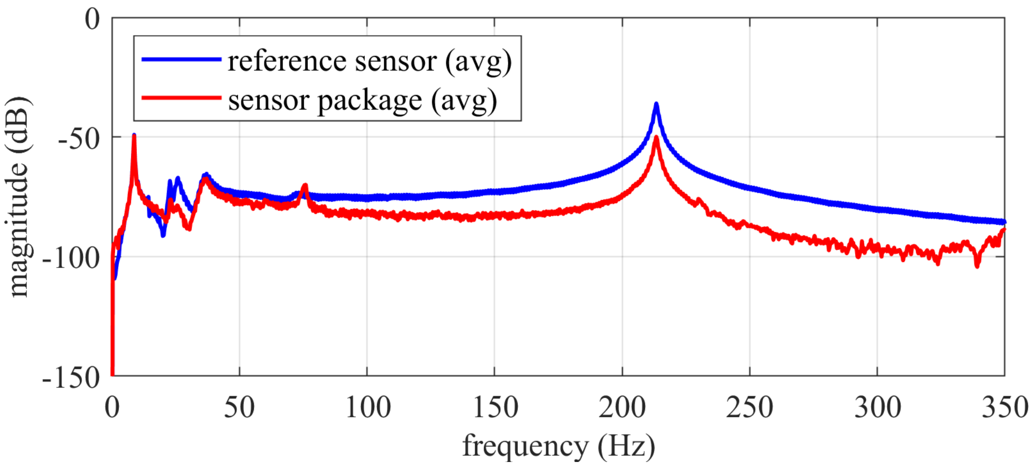

Figure 5. Averaged FFTs from each position during testing from the reference accelerometer.

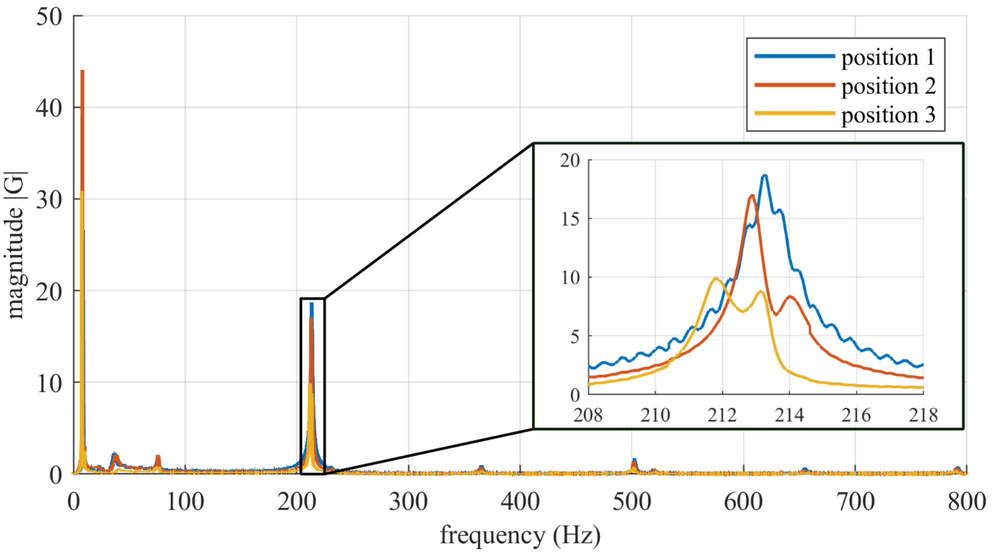

Figure 6. Averaged FFTs from each position during testing from the package.

RESULTS AND DISCUSSION

In this section, the results and findings of the modal-frequency shift experiment shown in Figure 4 are presented. Additionally, a frequency domain analysis of the impulse response test is conducted where the sensor package data is examined against a superior reference accelerometer.

When examining the frequency response of the sensor package in comparison to the reference accelerometer, presented in Figure 5 it is shown that the sensor package is able to detect the modal peaks accurately, however, the package's accelerometer fails to capture the vibration magnitude accurately. This attenuation can be attributed to both

TABLE I. Averaged peak frequency and magnitude from sensor package tests

Position	Frequency (Hz)	Magnitude (G)	Test Count
1	213.02	18.68	3
2	212.63	17.05	3
3	212.11	9.91	3

the transmissibility losses through the frame housing the MEMS accelerometer onboard the sensor package and the limited resolution of its analog-to-digital converter when compared to the high-fidelity reference accelerometer.

After validating the sensor package's ability to detect the desired modal frequency accurately, the frequency responses of the three roller positions, shown in Figure 3 are examined. The results presented in Figure 6 indicate that the package is able to detect a shift in frequency with the peak detection algorithm results reported in Table I

CONCLUSION

This work demonstrates the feasibility of using UAV-deployed edge sensors to detect frequency-based indicators of state changes in structures. The embedded FFT-based algorithm successfully tracked shifts in modal frequency resulting from support relocation, validating its effectiveness for real-time structural monitoring. By processing data locally and transmitting only peak frequency changes, the system significantly reduces power consumption, processing time, and communication overhead while maintaining diagnostic accuracy. These results underscore the potential of lightweight, autonomous sensor systems for scalable, rapid-response SHM in hard-to-access or hazardous environments.

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