Frequency-Based Damage Detection using Drone-deployable Sensor Package with Edge Computing

Ryan Yount[1], Joud N. Satme[1], and Austin R.J. Downey[1,2]

[1]Department of Mechanical Engineering
[2]Department of Civil and Environmental Engineering
University of South Carolina, Columbia, SC 29208

ABSTRACT
For rapid infrastructure assessment following natural and man-made emergencies, the utilization of minimally invasive and cost-effective drone deployable sensor packages has gained significant attention. While compact sensors with wireless data transfer capabilities have demonstrated potential for monitoring structural dynamics of critical infrastructure, such systems typically require data to be processed off-device and often off-site. These additional steps hinder the rapid assessment aspect. A challenge arises when transmission is not feasible due to degraded communication links during natural or man-made emergencies. Moreover, off-site data processing may add unnecessary delays to actions that can be taken by emergency personnel following infrastructure damage. To maximize the usefulness of sensor packages for rapid infrastructure assessment, the integration of edge computing techniques into the sensors themselves to analyze data in real time presents a promising solution. The objective of this work is to demonstrate edge computing for frequency-based structural health monitoring techniques to showcase the effectiveness of on-device data processing for the rapid assessment of infrastructure. The proposed approach continuously computes the power spectral density of windowed vibration measurements taken from a structure of interest that has the potential to experience further damage, for example, the monitoring of a bridge immediately after a flooding event. This work presents contributions in terms of a methodology, focusing on the hardware implementation of edge computing algorithms. Additionally, a study of the performance and resource utilization of a windowed power spectral density processing algorithm on-device is provided.

Keywords: edge computing, UAV, sensors, structural health monitoring, real-time damage detection

INTRODUCTION
The emergence of high mobility, compact sensing nodes has the potential to transform the landscape of SHM and modal analysis. These nodes, designed for deployment on unmanned aerial vehicles (UAVs) or other platforms, provide a unique advantage by combining rapid mobility with minimally invasive data collection, as shown in Figure 1. Utilizing unmanned deployment methods for these sensor nodes enhances personnel safety compared to conventional approaches, particularly when dealing with large structures [1]. This flexibility enables the swift deployment of sensors across a structure, facilitating dynamic data acquisition and structural assessment with remarkable efficiency. The integration of electropermanent magnets (EPM) and radio frequency (RF) communication into the sensing nodes proved beneficial to capturing the vibration signatures from remote and challenging-to-reach infrastructures. Edge computing allows for real-time processing of data at the source, which is critical for applications such as SHM. Instead of collecting data from sensors and processing it after a test, a sensor package that can process data locally can provide immediate insights into a system's structural condition. In this paper, we delve into an improvement of a pre-existing UAV-deployable sensing node. Leveraging EPMs and RF communication, this sensing node exhibits prowess in gathering vibration signatures from infrastructures located in difficult-to-reach locations. Positioned as

a wireless sensor network (WSN), these sensors reduce the challenge of high installation and maintenance costs associated with traditional wired methods [2]. Deployed via drones, these standalone sensors rapidly access structures using onboard accelerometers to collect data according to a preset schedule or event triggering for subsequent analysis. The comprehensive breakdown of the designed open-source sensing system is available in a publicly accessible repository [3].

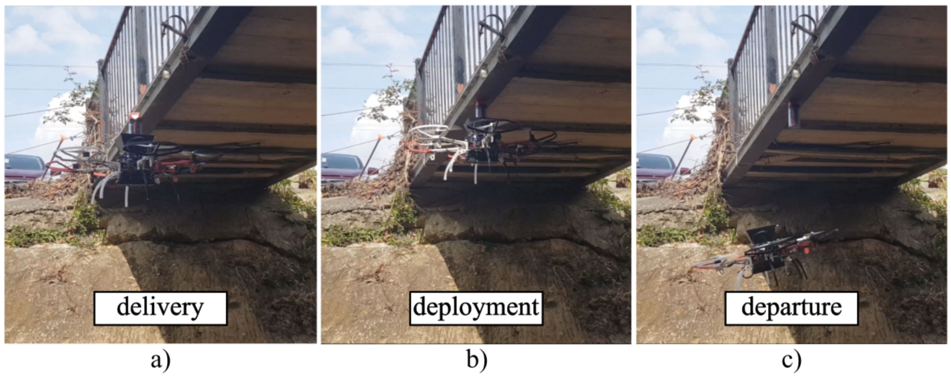

Figure 1: Different stages of sensor package UAV deployment with a) delivery b) deployment c) departure.

In this work, the integration of an edge-processing unit into this sensor network is introduced. Enhancements to the sensing system's real-time data analysis aspect is investigated, by leveraging edge-computing, to compute key features of the structure's dynamic response. This proposed procedure promises to further reduce the time affiliated with structural prognostics of the sensing system.

SENSOR DESIGN

The sensor package featured in this study represents an embedded system-based device, designed for long-term deployment, and equipped with several subsystems [4].

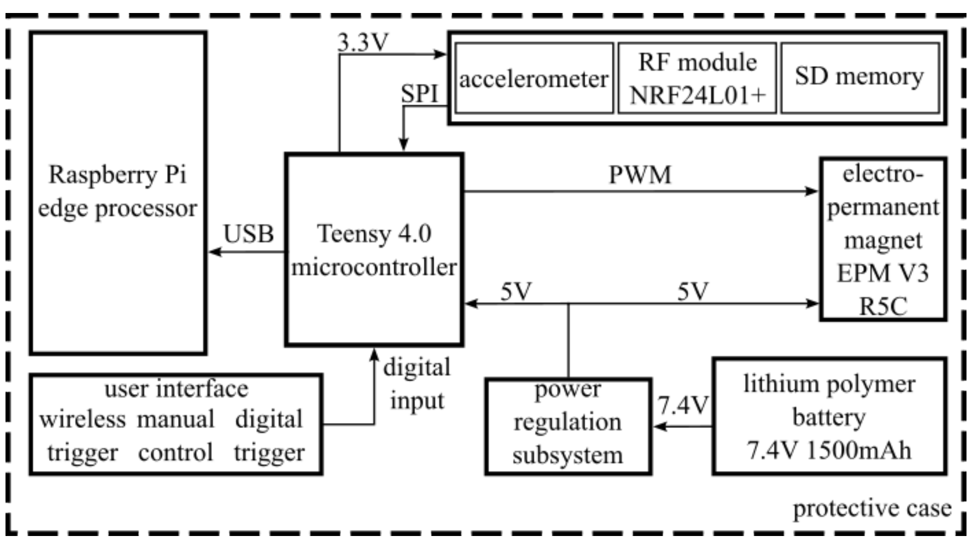

Figure 2: Block diagram of the components of the sensor package with the addition of the edge processor.

As shown in Figure 2, the processing core is an ARM-Cortex-M7, residing on a Teensy 4.0 microcontroller. To ensure sustained operation, the sensor package is provided with a 1500 mAh 2-cell lithium polymer battery, complemented by a dedicated power management subsystem that regulates voltage distribution to all other subsystems. Central to the sensor package's functionality is a high-performance MEMS accelerometer, the Murata SCA 3300-d01, which operates over the Serial Peripheral Interface

(SPI) protocol. For minimally invasive deployments, an EPM V3R5C NicaDrone electropermanent magnet is seamlessly integrated. These magnets, characterized by their low power consumption, require only a brief 5W pulse for state switching. This process is typically only performed twice per deployment. Facilitating wireless communication and command exchange is the Nordic Semiconductors NRF24L01 module, operating at 2.4 GHz via the ShockBurst protocol. This module offers the crucial capability of connecting with multiple sensor nodes simultaneously, which is desirable for effective wireless sensor triggering. To ensure precise data logging and trigger time referencing, the sensor package is equipped with a real-time clock.

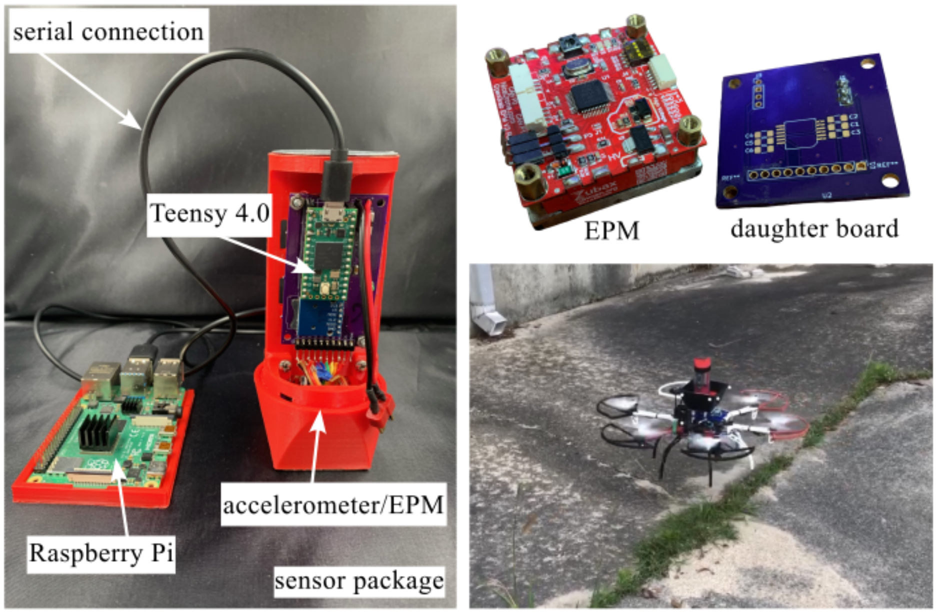

Figure 3: Sensor package with key components annotated along with a sensor package set up on a UAV.

Furthermore, data integrity is safeguarded through the incorporation of nonvolatile memory in the form of an SD card module. This ensures that valuable data is not lost in the event of power fluctuations or shutdowns. The sensor package is protected from the elements by its encapsulation within a protective 3D-printed PLA and PVC frame. This shields the delicate electronics from the harsh environment during field deployments as shown in Figure 3. The sensor package's footprint and weight have been optimized to be suited for UAV deployment [5].

EDGE COMPUTING ALGORITHM

In this section, the key features extracted from time-domain vibration data, along with a test and validation results are presented.

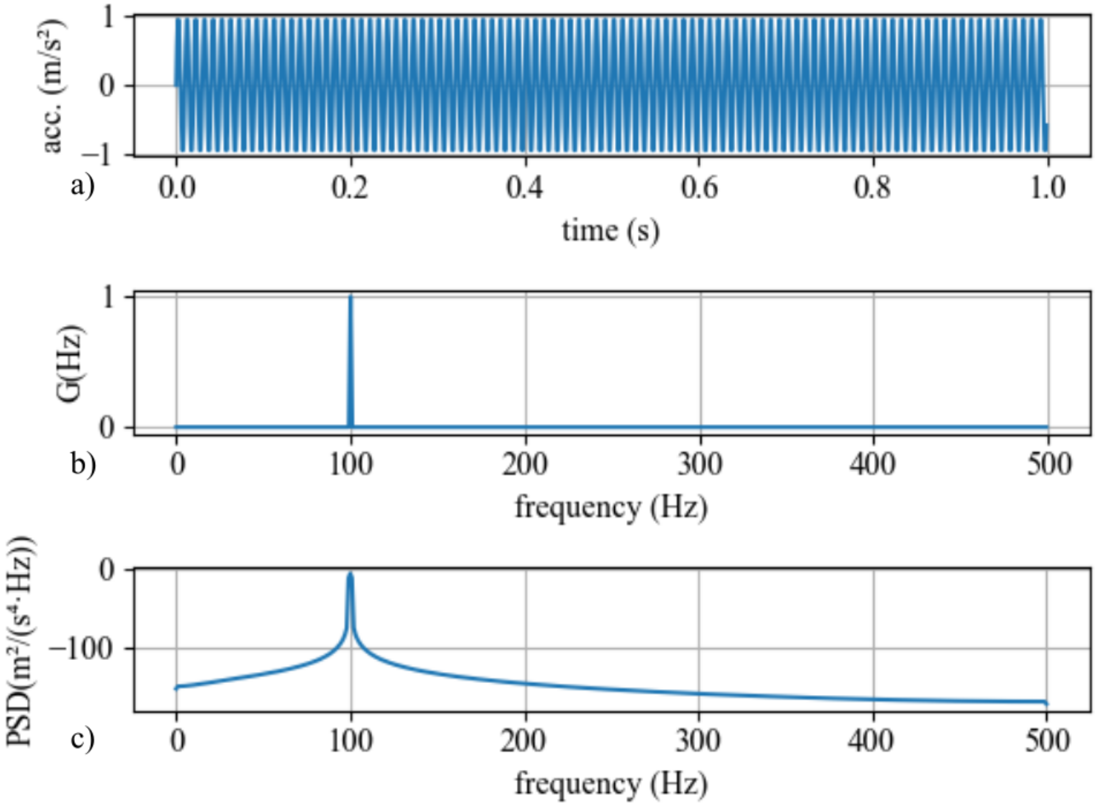

Figure 4: Synthetic data of a 100 Hz sinusoidal signal captured by the on-board edge-processor with a) time domain; b) FFT; c) PSD.

The Fast Fourier Transform (FFT) is a pivotal algorithm for the efficient computation of the Discrete Fourier Transform (DFT) applied to diverse datasets. Its application unveils the frequency components concealed within a time-domain signal. The FFT is often utilized in a spectrum of domains such as audio processing, image analysis, and the field of vibration analysis. This particular algorithm is extremely important to wireless sensor networks dedicated to structural health monitoring, as the extent of structural damage detectable through a system's dynamics is inversely related to the frequency range of excitation [6]. The FFT operation receives an extensive time-domain acceleration dataset obtained from the sensor nodes. This procedure undergoes a transformation of the data, shifting the signal from the time domain into the frequency domain. The signal is deconstructed into the various magnitudes of the frequency components. In many applications, only the positive frequency components are relevant, prompting the exclusion of the negative frequency bins. Consequently, the x-axis within Figure 4 represents the frequency components, while the y-axis showcases the magnitude of each frequency component to offer insight into the signal's dominant frequency components. In parallel, the Power Spectral Density (PSD) is an invaluable metric to elucidate the dispersion of power or energy across distinct frequencies within a signal. It is a key tool in various domains, including noise analysis, signal quality assessment, and vibration analysis, extending its applicability to the realm of wireless sensor networks employed for structural health monitoring. The computation for the PSD necessitates a precedent FFT calculation. Once the frequency components have been determined, the magnitude of the FFT coefficients is squared since the PSD conveys power and power is proportional to the square of the magnitude. Subsequently, the PSD values are normalized by dividing by the total signal length and the square of the sampling frequency. This normalization ensures the values are expressed in units of power per Hertz, providing a foundation for the analysis. To allow for a clearer representation of the power distribution across different frequencies, the values are articulated as decibels per Hertz.

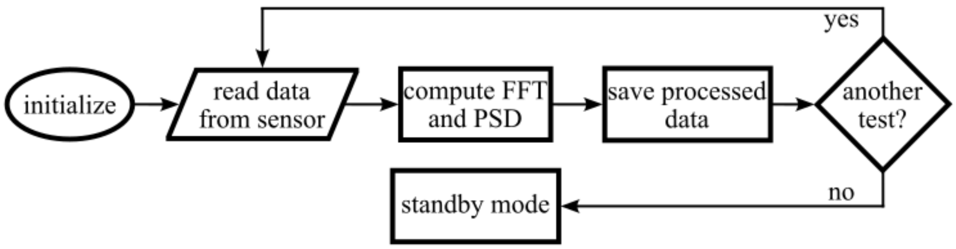

Figure 5: Flowchart of the code on the edge processor.

The Python code used on the edge processor is designed to perform a series of data processing and visualization tasks on real-time data received through a serial connection, typically from an external device like a sensor. As presented in Figure 5, the code establishes a serial connection between the sensor package's Teensy 4.0 and the edge-processing Raspberry Pi and reads incoming data. It collects pairs of time and acceleration values until the whole dataset is acquired. Once the full dataset is gathered, the FFT is computed to analyze the frequency components. Subsequently, the PSD is calculated to represent the distribution of power with respect to frequency in the system. The time-domain, FFT, and PSD results are then saved onto nonvolatile memory.

TESTING PROCEDURE

The primary objective of this experiment is to investigate the power consumption associated with various functions performed by the edge-computing system.

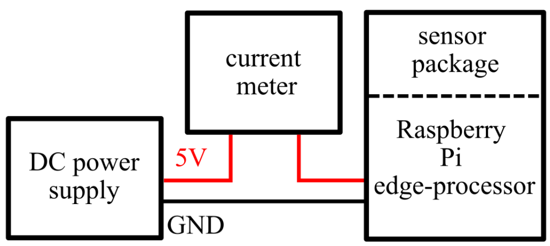

Figure 6: Block diagram depicting the power draw experiment with key components annotated.

As represented in Figure 6, the experimental setup consists of several components, including a DC power supply, an ammeter in series to measure current, an edge computing platform (Raspberry Pi), a sensor package (Teensy 4.0) with serial communication capabilities, and a data logger to record temporal power consumption. The software code developed for this experiment encompasses four essential tasks: firstly, the initialization of the edge computing platform; secondly, the continuous reading of data from the sensor package through se-rial communication; thirdly, signal processing to generate frequency response and power spectral density information; and lastly, the storage of processed data into memory for analysis. Once the serial data stream is completed, the edge processor transitions into standby mode to conserve energy. This experiment serves as a valuable tool to gain insights into the computational power requirements for extracting crucial features from time-domain data sent serially to the edge computing device, thereby aiding in optimizing energy-efficient edge computing solutions.

RESULTS AND DISCUSSION

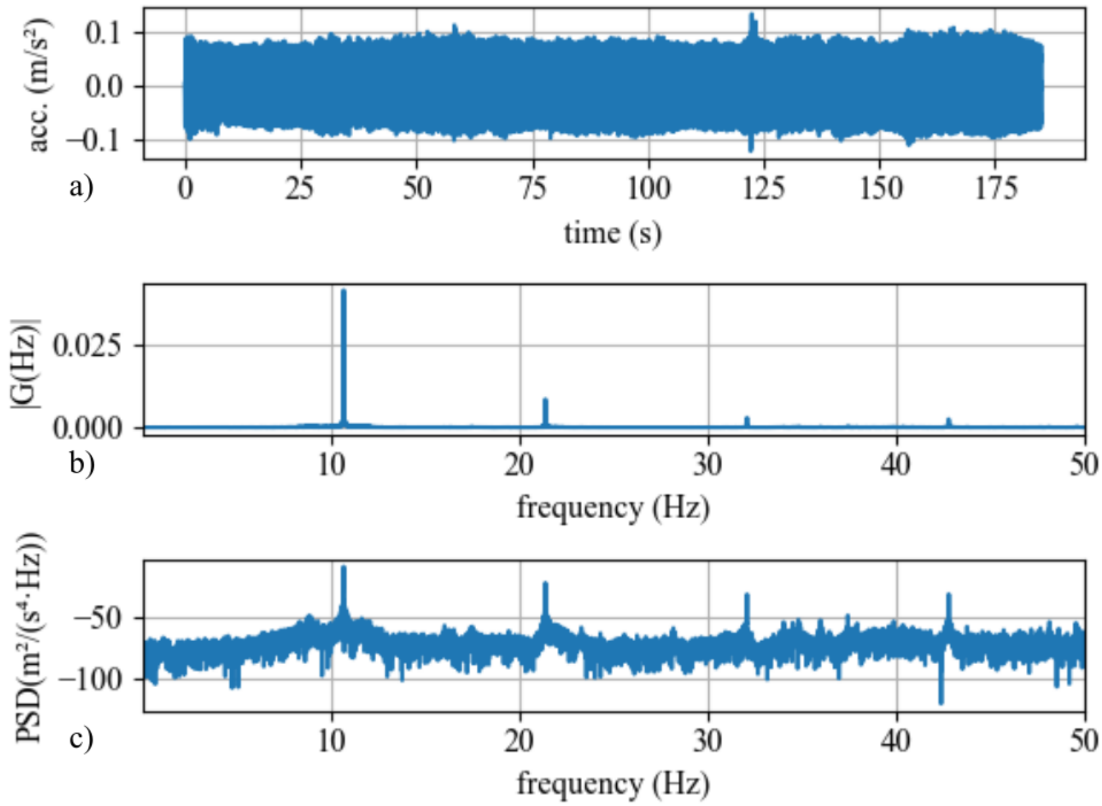

Figure 7: Vibration response of data captured by the sensor package deployed on a real structure, with the edge-processor capturing a) time domain; b) FFT; c) PSD of the structure under excitation.

In order to validate the effectiveness of the edge processor, a practical test using real acceleration data obtained from a bridge through the sensor package was conducted. The edge processor was able to analyze this data, providing plots in the form of the time domain, FFT, and PSD as shown in Figure 7. This real-world application demonstrated the processor's ability to swiftly process structural data under continuous excitation conditions.

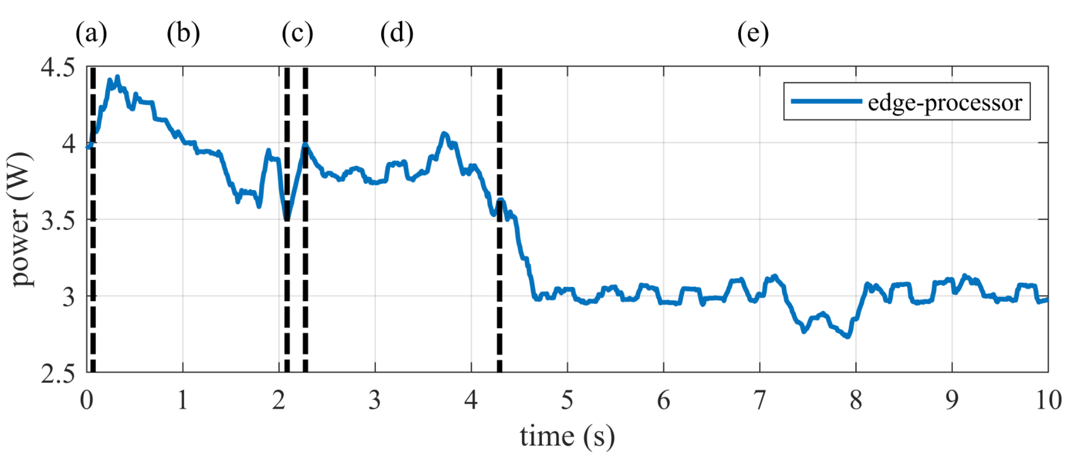

Figure 8: Power draw of the edge processor sectioned into: (a) initialization; (b) reading data; (c) computing the FFT and PSD; (d) saving the processed data, and; (e) standby mode.

In the power consumption testing of the sensor package with the integrated edge computing processor, several observations were made. The power consumption profile exhibited distinct phases during operation, as shown in Figure 8. Upon initialization, the system's power usage climbed to approximately 4 watts as the sensor package and edge processor powered up. Subsequently, during data collection, the power draw spiked to around 4.4 watts until gradually decreasing to less than 4 watts. During the data processing phase, where the processor computes the FFT and PSD of the captured data, power consumption increased slightly to roughly 4 watts again. Following data processing, the processor saved the computed data, maintaining a power usage in the range of 3.7 to 4.1 watts. Finally, when the sensor package entered standby mode, awaiting the initiation of the next test, power consumption remained at approximately 3 watts. The results of power consumption testing with the newly integrated edge processor within the sensor package strongly support the viability of edge processing as a favorable alternative to active retrieval of data. Although the power consumption of the edge processing system could be improved, the sensor package can still perform calculations with efficiency that is crucial for real-time structural analysis. Performing these calculations on the edge reduces data transfer delays associated with physical retrieval and processing of captured data from infrastructure.

CONCLUSION

In this work, the addition of an edge processor on an embedded system-based high-mobility sensor network is examined. During viability testing, the power consumption results underscore the effectiveness of edge processing in terms of energy efficiency, data accessibility, and reduced processing delays. These advantages showcase edge processing as a valuable alternative to active data retrieval, particularly for applications where resource constraints, remote deployment, and real-time anal-ysis are critical considerations. The system under investigation holds the potential for extensive deployment, offering a means for swift assessment of infrastructure in the aftermath of severe weather events. This deployment can quickly deliver initial insights into the condition of the infrastructure. While the system currently presents a viable solution, there are still avenues for future improvement. Notably, despite the sensor's relatively compact size, the inclusion of the edge processor significantly expands the footprint. Subsequent research will explore the utilization of smaller edge processors to further reduce the size and power consumption of the sensor package. Additionally, future work will delve into employing edge processors across multiple sensor packages within a network. This approach aims to enable rapid computation across an entire structure, rather than relying on a single localized point for processing.

ACKNOWLEDGEMENTS

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