Case Study for Using Open-Source UAV-Deployable Wireless Sensor Nodes for Modal-Based Monitoring of Civil Infrastructure

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ABSTRACT

Experimental modal analysis is an important technique used in structural health monitoring to evaluate the dynamic properties of a structure, such as natural frequencies, damping ratios, and mode shapes. There has been an increasing interest in using uncrewed aerial vehicles (UAVs) to perform experimental modal analysis, as they offer several advantages over traditional hardwired sensing systems. UAVs equipped with deployable wireless sensor packages can capture a vast amount of data due to their high mobility, enabling the identification of subtle structural behaviors that would be more challenging to obtain using conventional sensors. This case study focuses on the use of UAV-deployable wireless sensor nodes to perform experimental modal analysis on a pedestrian bridge in use.

The objective of this study is to demonstrate the potential for monitoring the dynamic properties of a structure using networks of UAV-deployable sensor packages. The paper reports on the development of an open-source UAV-deployable sensor node designed for autonomous deployment on steel structures. The open-source sensor package is a standalone system that includes independent energy storage along with nonvolatile memory and radio frequency communication capabilities. A high-performance microcontroller is utilized to record and process acceleration data in real-time. Moreover, the microcontroller processes various input/output commands, manages the transmission of status updates, and controls the electropermanent magnet onboard during the docking procedure in combination with the UAV to ensure safe deployment.

The case study consists of an experimental approach, using a vibration-based sensing network in conjunction with a structural shaker, to capture the structural dynamics of a pedestrian bridge under forced excitation. The results showed that the UAV-deployable wireless sensor nodes were able to capture accurate and reliable data, enabling the identification of the bridge's first flexural mode shape. Furthermore, this study provides valuable insights into the challenges and prospects associated with using UAV-deployable sensors for the dynamic modeling of structures in a structural health monitoring framework.

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INTRODUCTION

Structural Health Monitoring (SHM) involves measuring the structural properties of a system to assess its current condition. It is a nondestructive inspection technique that relies on sensor measurements, with the aid of damage detection algorithms, to infer the state of a structure [1]. By accurately quantifying and localizing early signs of damage, SHM helps to extend the operational lifespan of infrastructure. Enabling early maintenance to be performed, the risk of catastrophic failure is reduced while minimizing downtime and lowering repair costs.

Modal analysis is extensively employed in SHM applications due to its ability to provide insights into the dynamic characteristics of a structure. By observing alterations in the dynamic response, potential damage and deterioration can be detected and localized. Studies on the use of vibration-based sensing networks indicate the ability to infer the state of a structure by tracking the structural modes and their natural frequencies. This involves monitoring changes in the structural dynamics over extended periods of time, which can indicate the occurrence of damage [2]. Vibration-based SHM techniques can be categorized into two classes, passive and active, where the two approaches are similar in data gathering and sensors used, the primary difference lies in the excitation source. Passive vibration-based SHM relies on unknown and random excitation such as wind interaction with tall towers or passing vehicles over a bridge, whereas active SHM makes use of a known excitation signal fed into the structure by actuators or transducers. With the ability to control the characteristics of the excitation signal, the response to specific conditions can be investigated with minimal interference. Monitoring a structure passively simplifies the approach and enables rapid assessment, however, the unpredictable excitation source along with the low magnitude of the response, which requires high-resolution sensors, makes the analysis challenging. Although the networks of sensors and actuators required for active SHM are high in complexity, especially in inaccessible locations, this method enables the study of specific dynamic responses which results in the accurate capturing of mode shapes and their natural frequencies. Efforts into miniaturization and autonomy have been put forward to streamline active structural health monitoring and increase the remote and rapid deployment capabilities as demonstrated by [3].

SHM of infrastructure has numerous approaches to observe deterioration patterns and quantify damage over a structure's operational lifespan. Notable methods rely on visual inspections, acoustic emissions sensing, digital twin models, and vibration-based techniques [4–7]. SHM of civil infrastructure presents many challenges that this work attempts to address. First being the large size of civil structures, as modal-based prognostics require a high number of sensing nodes on the structure to accurately detect and reconstruct the modes. Additionally, hard-wired and permanently mounted sensors present another challenge as these systems require installation and trained personnel which can be costly and hazardous. Another obstacle to civil infrastructure monitoring is the location of such structures. Remote and hard-to-reach structures, suspended bridges, and high voltage pylons for example, can be located on unhospitable terrain where approaching the structure conventionally is difficult and unsafe. In an aim to rectify the addressed challenges, this work presents a network of UAV-deployable sensing nodes with wireless long-range capabilities for modal-based SHM applications. The contributions of this work are twofold. 1) A report on the capabilities of an open-source UAV-deployable vibration-based sensing network with wireless communication, 2) A case study on active mode detection using the sensing network along with a structural excitation shaker.

METHODOLOGY

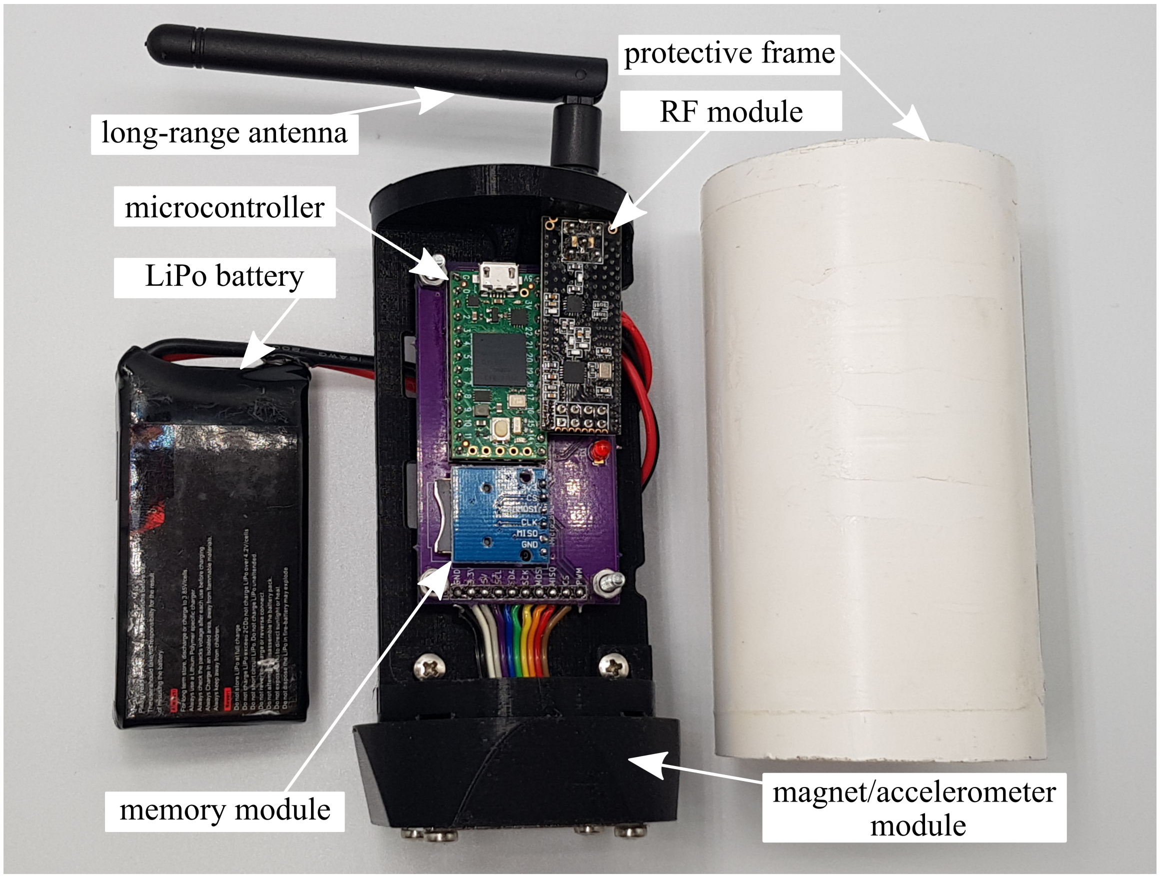

Figure 1. Open-source vibration sensor package with key components annotated.

To effectively capture the modal response of a structure utilizing a network of vibration sensors, a previously developed open-source UAV-deployable sensor package [8] that has demonstrated modal-monitoring capabilities in a laboratory setting [9] was enhanced with long-range wireless communication to enable its use on real-world steel structures. The developed open-source UAV-deployable sensor package is shown in figure 1 and is comprised of a microprocessor, accelerometer, independent memory, real-time reference, and the aforementioned long-range wireless capabilities. Design files for the sensor package are available in a public repository [10]. The package incorporates an ARM Cortex-M7 microprocessor on a Teensy 4.0 microcontroller. It is powered by a two-cell 1500 mAh lithium polymer (Li-Po) battery, supported by a power management system to regulate and ensure steady voltage to the various subsystems. Data from a high-performance SCA-3300 MEMS accelerometer is collected and stored in a nonvolatile memory module using the Serial Peripheral Interface (SPI). The package is also equipped with a DS3231 real-time clock (RTC) for precise time reference, and RF communication through an NRF24L01+ for wireless triggering and data transfer. The system is housed in a 3D-printed PLA frame to shield the delicate electronics during deployment. A long-range wireless transmitter was also developed using the same framework as the package, with the inclusion of a high-power RF amplifier with a gain of 40 dB. This amplifier was daisy-chained to the onboard amplifier of the NRF24L01+ module, enhancing the range and reliability of the wireless network. The transmitter was developed to enable the user to synchronize sensing nodes during deployment. This aids in capturing structural mode shapes more accurately by reducing sensor-related phase shifts caused by transmission latency.

To seamlessly integrate with UAV deployment, the system is developed to incorporate EPM-V3R5C electropermanent magnets (EPMs). EPMs are preferred for such applications due to their low power consumption and non-invasive nature on the host structure [11]. The activation of magnetization or demagnetization configuration only requires a one-second pulse of approximately 5 W. This process is typically performed twice during deployment – once when securing the package to the structure and again when detaching it. The UAV is also equipped with a retrieval harness designed to securely hold the package during flight. The retrieval harness incorporates its own EPM with magnetization and demagnetization capabilities for retrieval and deployment, respectively.

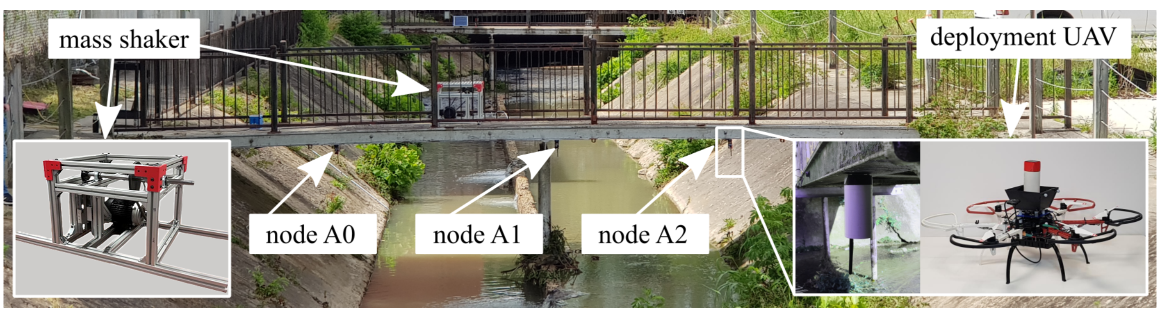

Figure 2. Sensor network placement along with the mass shaker on the test bridge and the UAV deployment system.

To investigate the dynamic response of a pedestrian bridge in this study, an experiment was devised. Adopting an active analysis approach, a structural mass shaker, shown in figure 2, is utilized. The mass shaker converts rotational motion from a 3-phase AC motor into linear oscillations, inducing vibration in the structure. During testing, the mass shaker is placed on the structure along with the sensing network. Data collection is initiated using the long-range wireless transmitter. Once the network is operational, a frequency sweep excitation in the range of 0 to 20 Hz is applied to the structure through the shaker to lock onto the frequency response of the highest magnitude. The sensors are then mobilized across the bridge to explore regions with the highest measured response magnitudes. Identifying the regions with the strongest response provides valuable information about the locations of the antinodes of a desired mode shape. The frequency bandwidth used in this experiment specifically targets the detection of the first flexural mode of the test structure.

RESULTS AND DISCUSSION

In this section, the results of the proposed experiment are presented along with a discussion on system limitations in addition to the experimental outcomes.

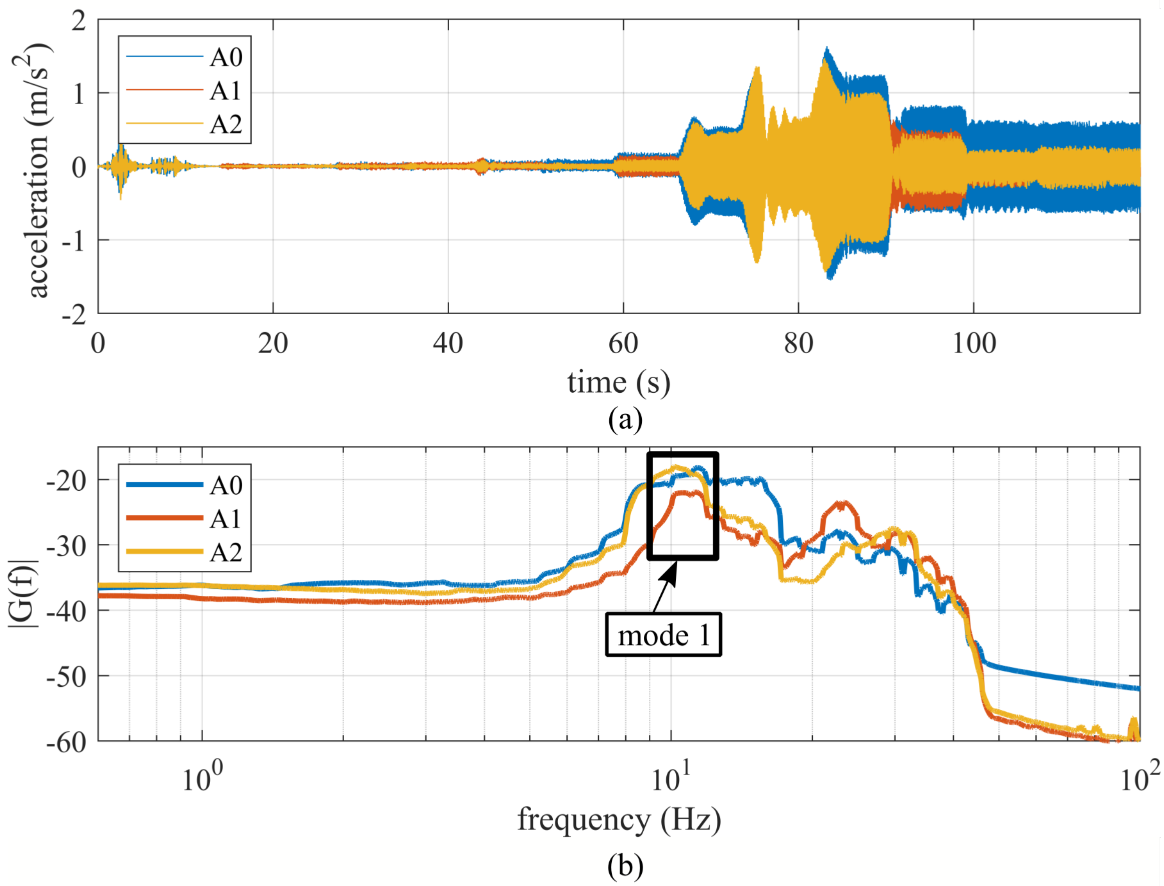

Figure 3. Experimental results of the pedestrian bridge modal detection experiment using a mass shaker for active excitation with (a) time domain measurements, (b) frequency domain response with the first flexural mode identified

Using the sensing nodes as probes, the structure is scanned for critical regions. As depicted in Figure 2, the sensors are strategically placed at A0, A1, and A2 to target the first flexural mode. In Figure 3 (a), the captured acceleration signatures from the three sensor packages are displayed. Both A0 and A2 sensing nodes are positioned at the antinodes, while A1 is placed near the central support of the bridge. The frequency sweep reveals a prominent response at 10.51 Hz, corresponding to the first flexural mode. Examining Figure 3 (b), it can be observed that both A0 and A2 exhibit higher oscillations compared to A1, which experiences a lower response due to its proximity to a fixity in this specific test configuration. Further analysis of the frequency domain reveals complex responses within the bandwidth of 20-50 Hz, attributable to higher modes of the structure.

The challenges encountered in this case study are associated with conducting tests on metal structures, which generate induced magnetic fields that interfere with the wireless network. To address this issue, increasing the transmission power and implementing an RF filter onboard the sensor packages to enhance the signal-to-noise ratio (SNR) effectively rectify any interference. The presented results exemplify the application of an active structural health monitoring system for capturing the first flexural mode of a pedestrian bridge. The utilization of an open-source sensing network, combined with a long-range transmitter and a mass shaker, demonstrates promising potential due to their high mobility and reliability during testing.

CONCLUSION

Experimental modal analysis is an essential technique in structural health monitoring, and uncrewed aerial vehicles (UAVs) have emerged as a promising platform for its implementation. By utilizing UAVs equipped with deployable wireless sensor packages, a vast amount of data can be captured, enabling the detection of subtle structural behaviors that are challenging to obtain using conventional sensors. The objective of this study was to demonstrate the potential of monitoring the dynamic properties of structures using networks of UAV-deployable sensor packages. The case study involved the use of a vibration-based sensing network and a structural shaker to capture the dynamic response of a pedestrian bridge under forced excitation. The results provided valuable insights into the challenges and prospects associated with employing UAV-deployable sensors for dynamic modeling in a structural health monitoring framework. In conclusion, this study successfully implemented an active structural health monitoring system for capturing the first flexural mode of a pedestrian bridge. The combination of a mass shaker, open-source sensing network, and long-range transmitter allowed for targeted scanning of key regions, localization of antinodes, and identification of the first flexural mode frequency. This research contributes to advancing structural health monitoring techniques and enhancing the safety and longevity of infrastructure.

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